ANNUAL INNOVATION ISSUE

TECHNOLOGY REVIEW

FEBRUARY 2001

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John Seely Brown
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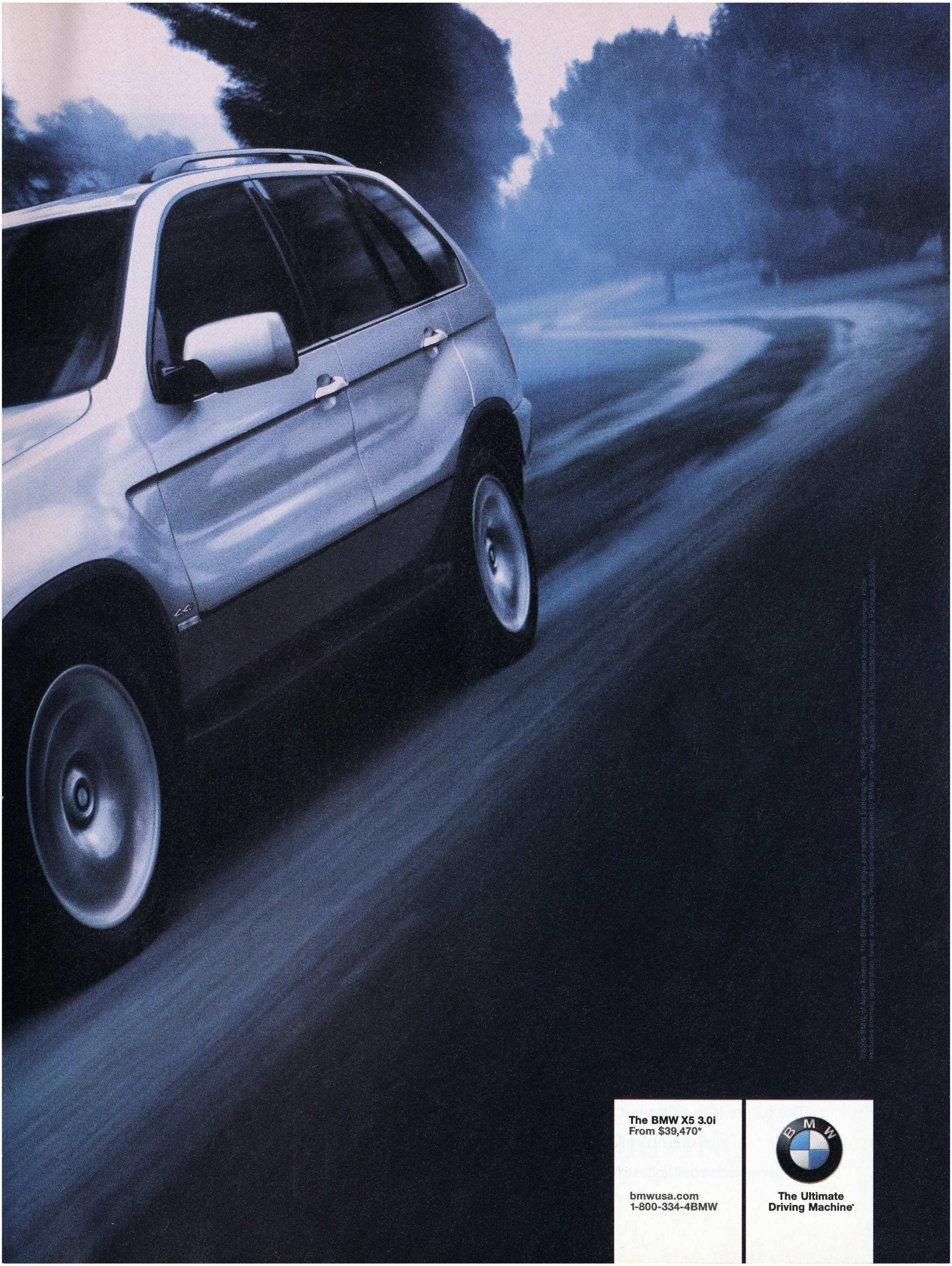

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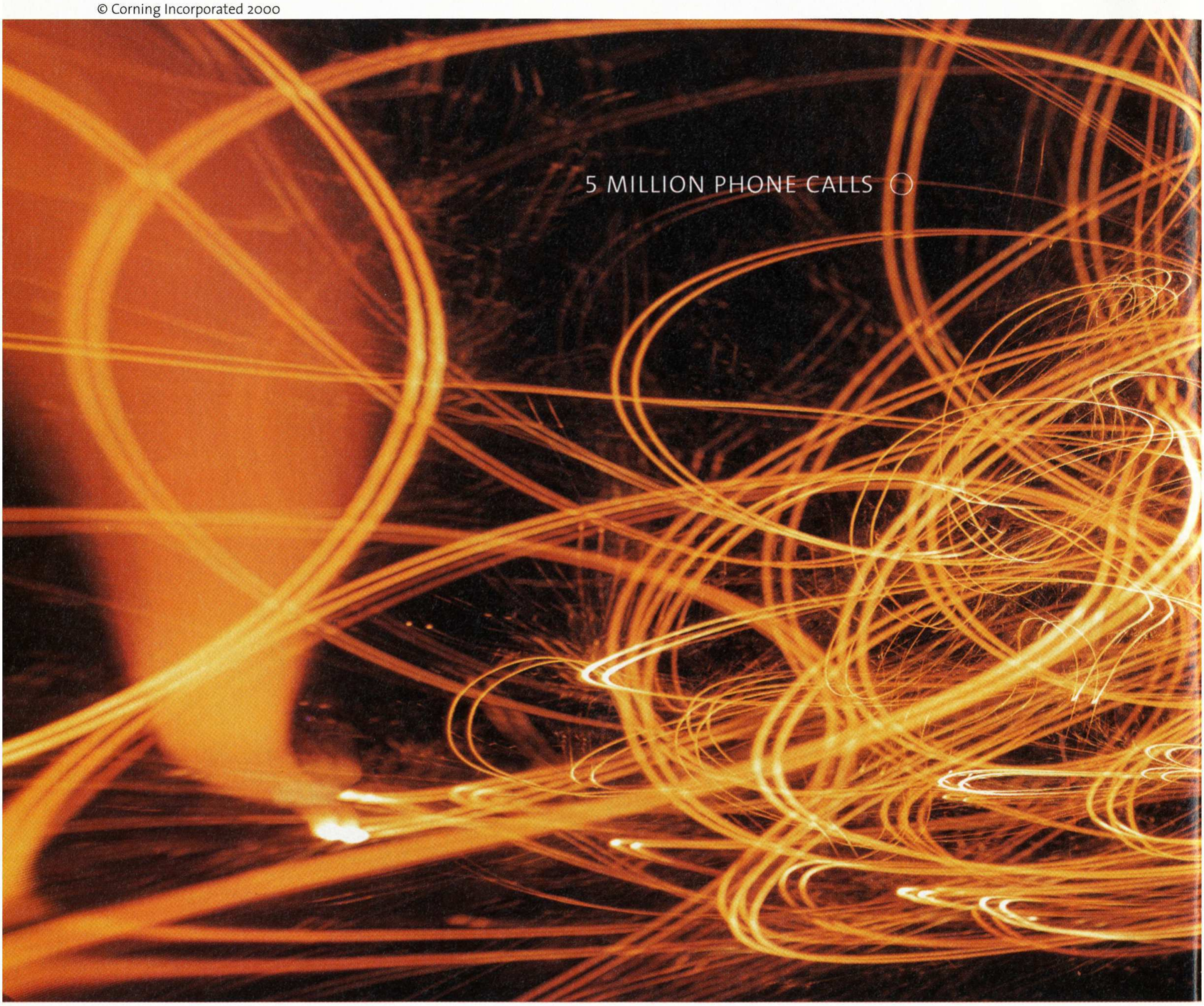

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From online movies to business transforming Internet applications.

The future is exciting but unknowable. But one thing is for certain:

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The superfast, superbroad boulevards of light coming out of Corning.

A selection of Goldman Sachs advised mergers and acquisitions.

MARVELL
Marvell Technology Group Ltd.
has agreed to acquire
Galileo Technology Ltd.
Pending

EXODUS
has agreed to acquire
Global Crossing's GlobalCenter Inc.
Pending

CORNING
has acquired
NetOptix Corporation
May 2000
has agreed to acquire
Pirelli S.p.A.'s stake in Optical Technologies
Pending

COBALT NETWORKS
has agreed to be acquired by
Sun Microsystems, Inc.
Pending

CLUSTER
has agreed to combine with
Diamond Technology Partners Incorporated
Pending

PEARSON
has agreed to acquire
National Computer Systems
Pending

SLP Silver Lake Partners
and
Veritas Software Corp.
have agreed to acquire
Seagate Technology, Inc.
Pending

ARROW
has acquired the
Wyle Companies
from
E.ON AG
October 2000

ORIGIN
Philips' IT Services Subsidiary
has merged with
ATOS
October 2000

Inktomi
has acquired
FastForward Networks
October 2000

Active Software
has been acquired by
WebMethods, Inc.
August 2000

ANCOR Communications, Inc.
has been acquired by
QLogic Corporation
August 2000

LHS
has been acquired by
Sema Group plc
July 2000

tsmc
has acquired
Worldwide Semiconductor Manufacturing Corporation
July 2000
has acquired
TSMC-Acer Manufacturing Corporation
July 2000

E-TEK DYNAMICS
has merged with
JDS Uniphase Corporation
June 2000

ArrowPoint Communications
has been acquired by
Cisco Systems, Inc.
June 2000

i2
has acquired
Aspect Development, Inc.
June 2000

CAP GEMINI
Ideas People Technology
has acquired the
IT consulting businesses of
Ernst & Young
May 2000

Kana Communications
has acquired
Silknet Software, Inc.
April 2000

BROADVISION
Personalizing e-Business
has acquired
Interleaf Inc.
April 2000

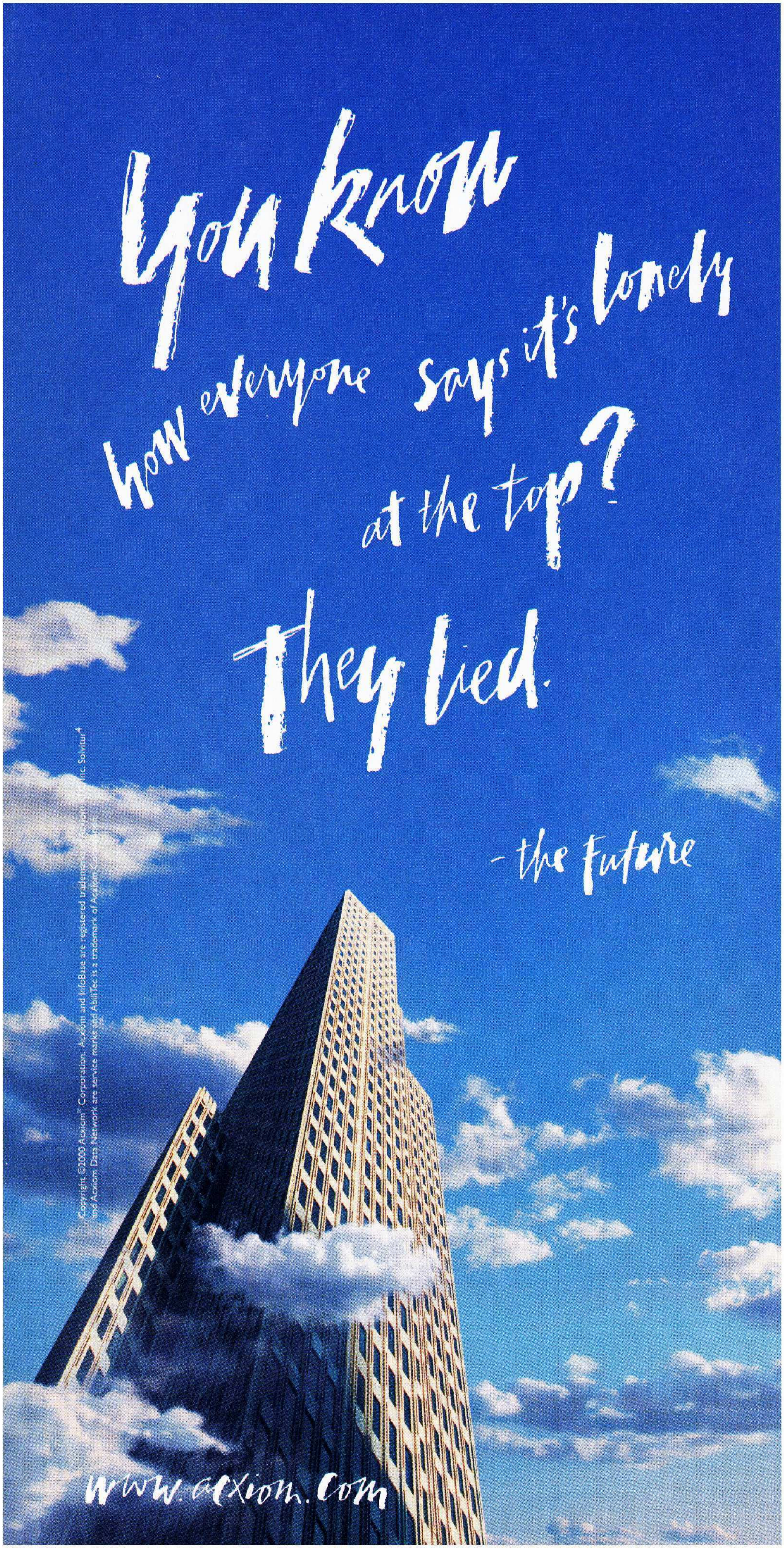
onebox.com
has been acquired by
Phone.com Inc.
April 2000

Amdocs
has acquired
Solect Technology Group Inc.
April 2000

STERLING SOFTWARE
has been acquired by
Computer Associates International, Inc.
March 2000

STERLING COMMERCE
has been acquired by
SBC Communications
March 2000

CISCO SYSTEMS
has acquired the
Optical Systems Business
of
Pirelli S.p.A.
February 2000



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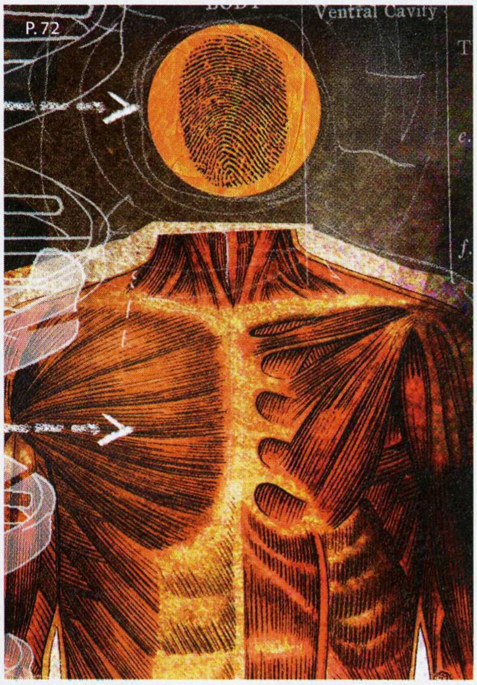
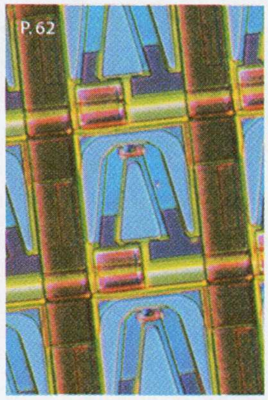
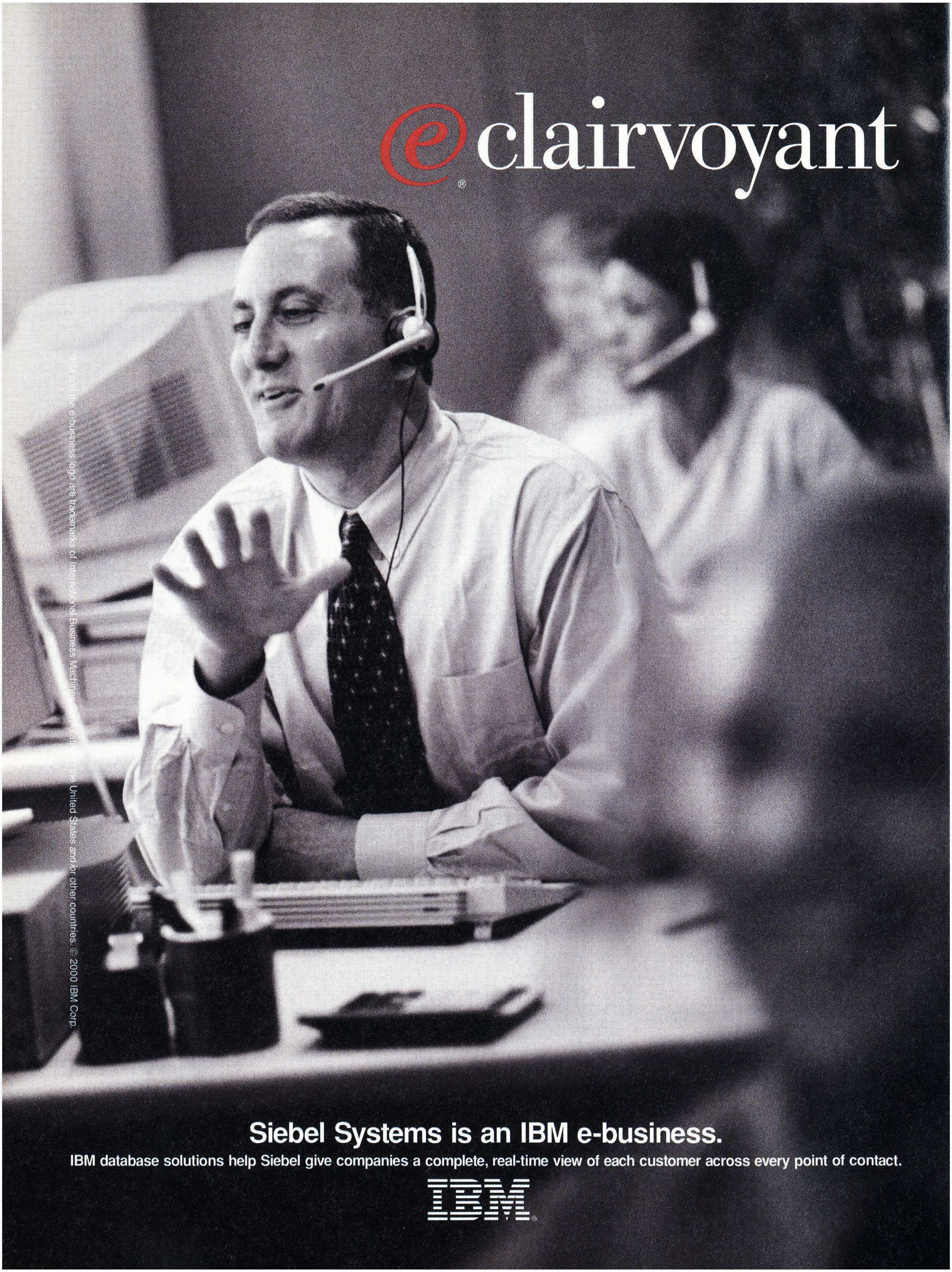




EMERGING TECHNOLOGIES 10 THAT WILL CHANGE THE WORLD

FEATURES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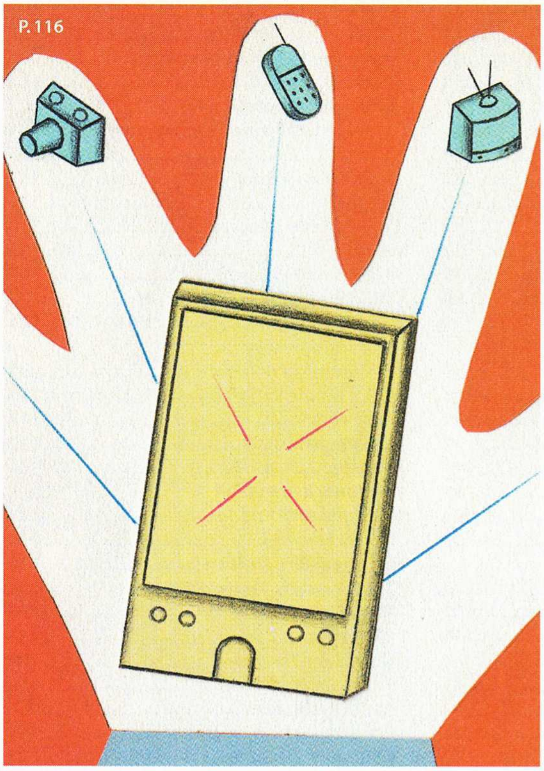

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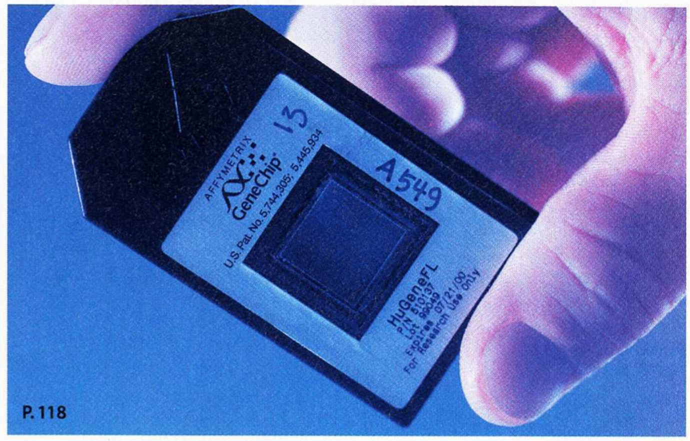

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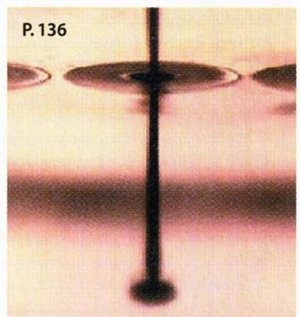

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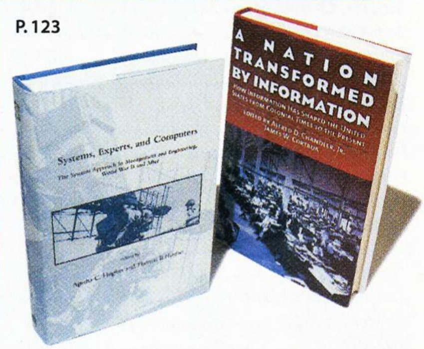

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COLUMNS

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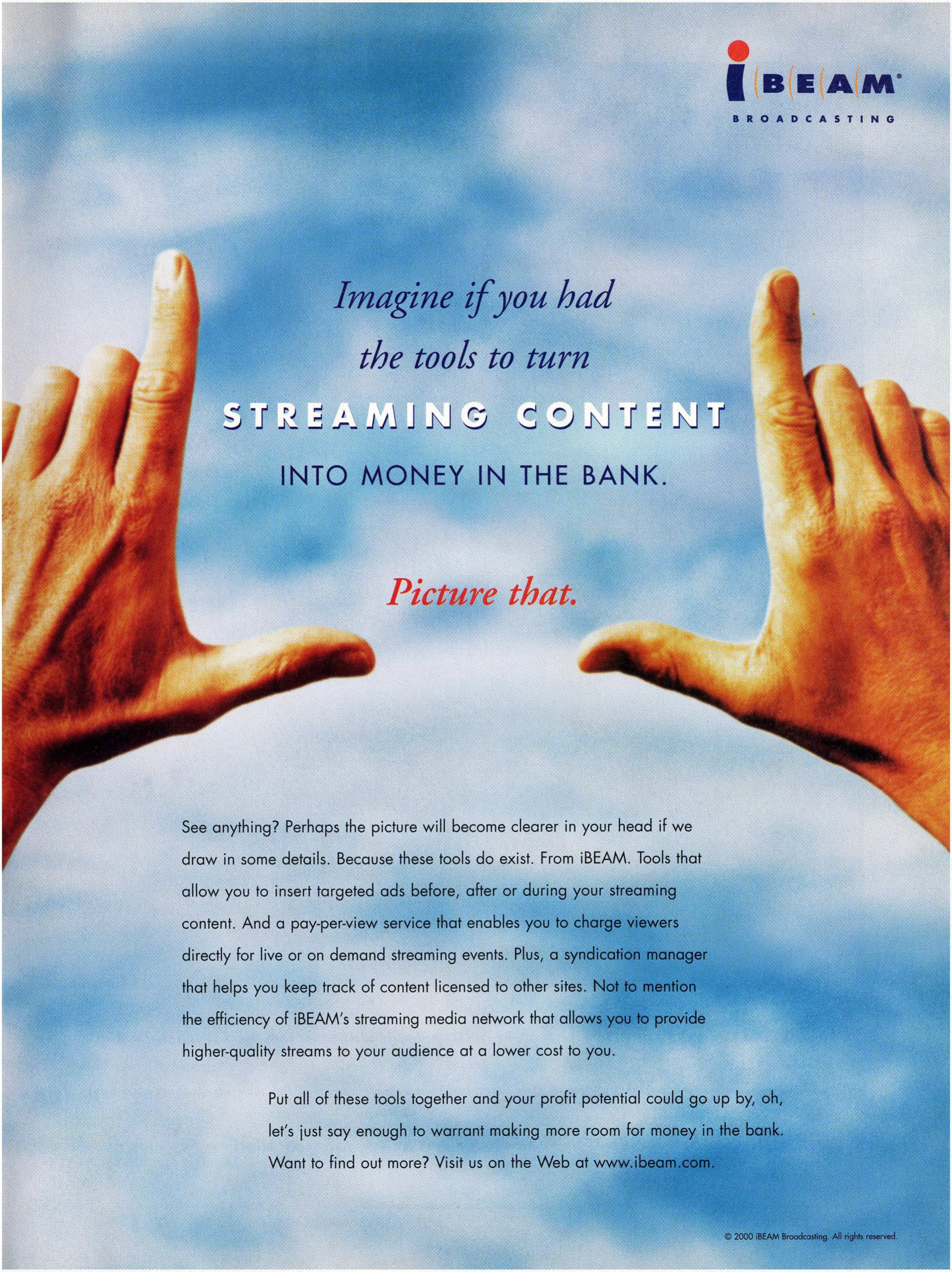
PEOPLE

ORGANIZATIONS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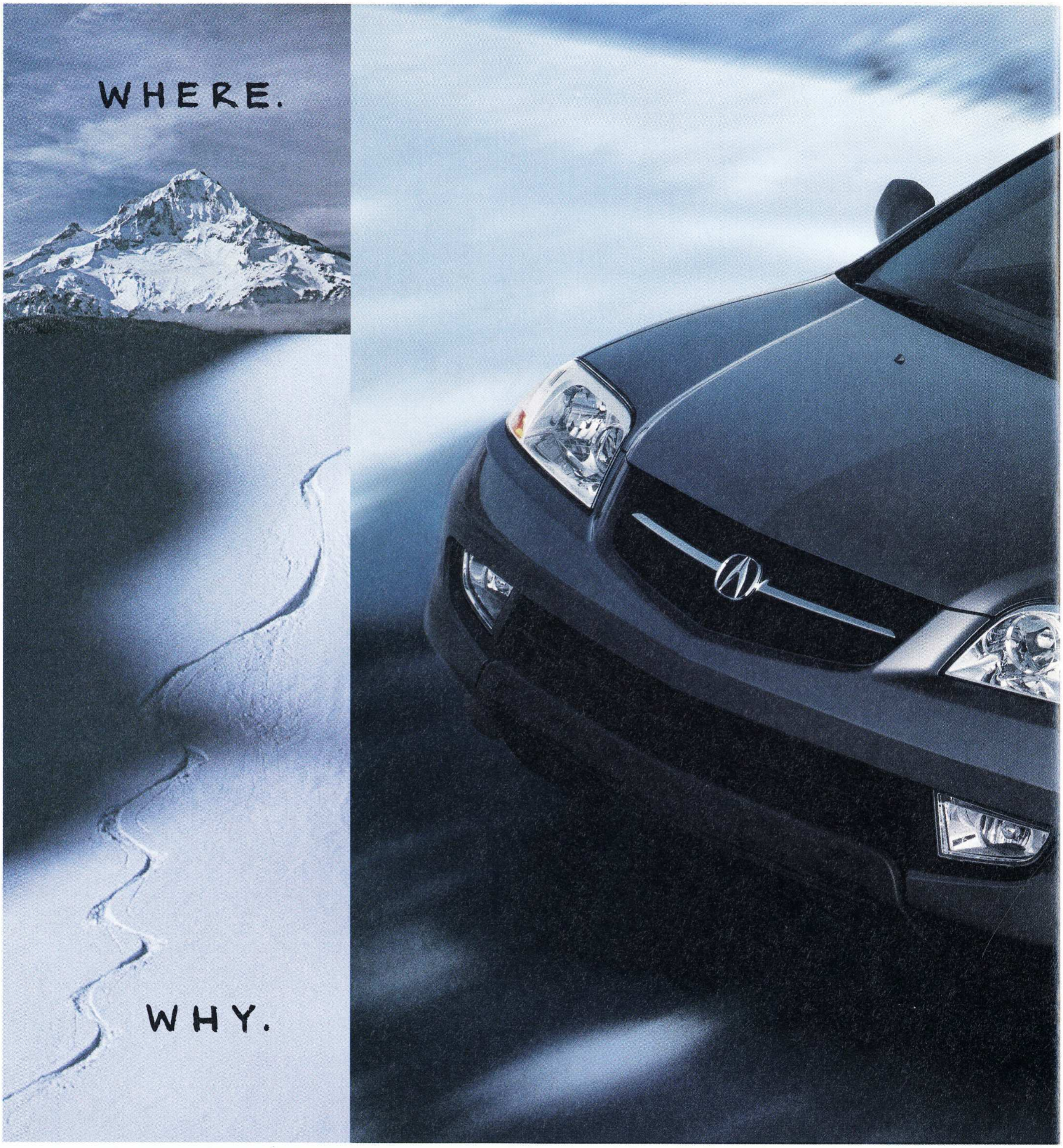

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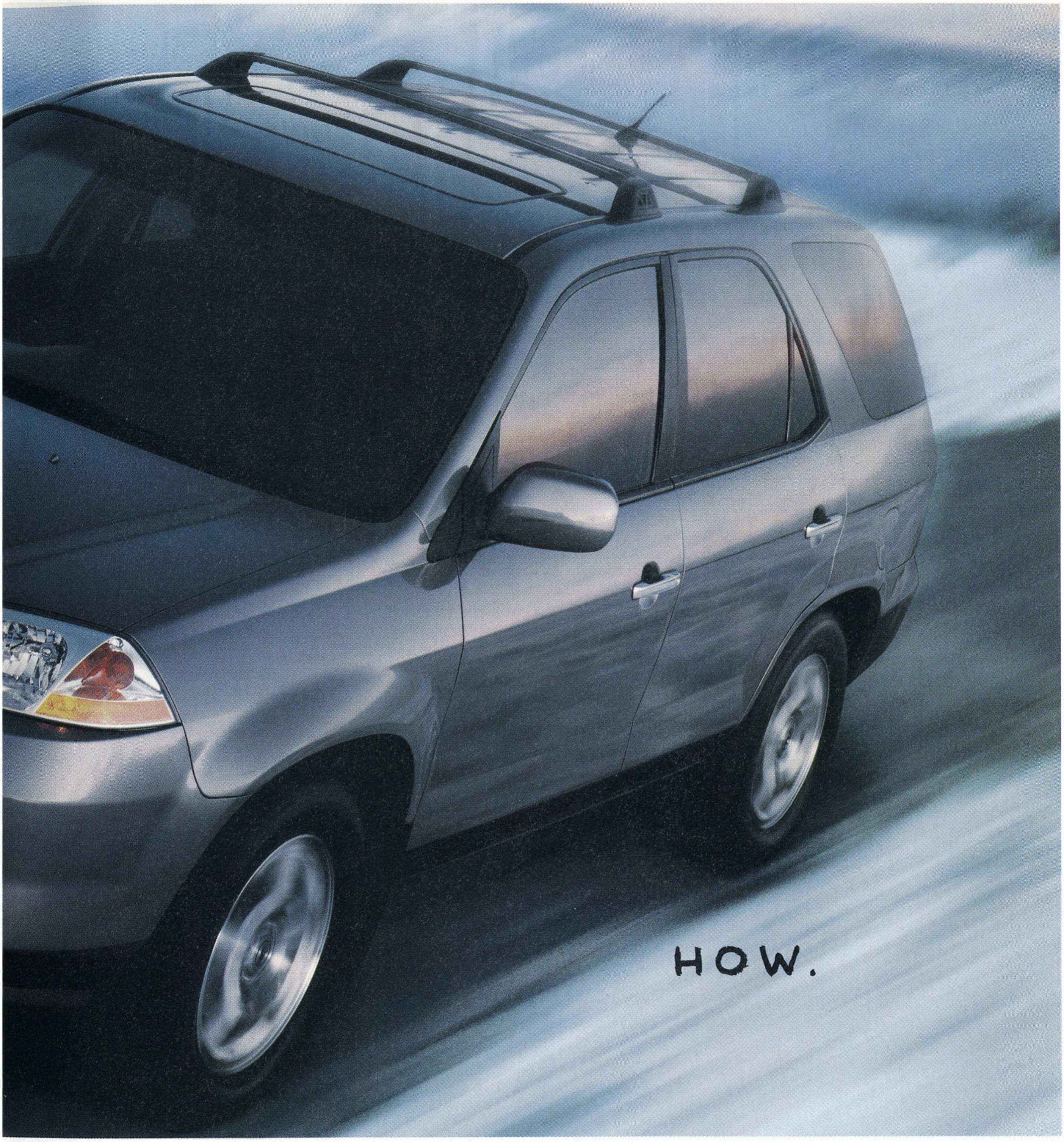

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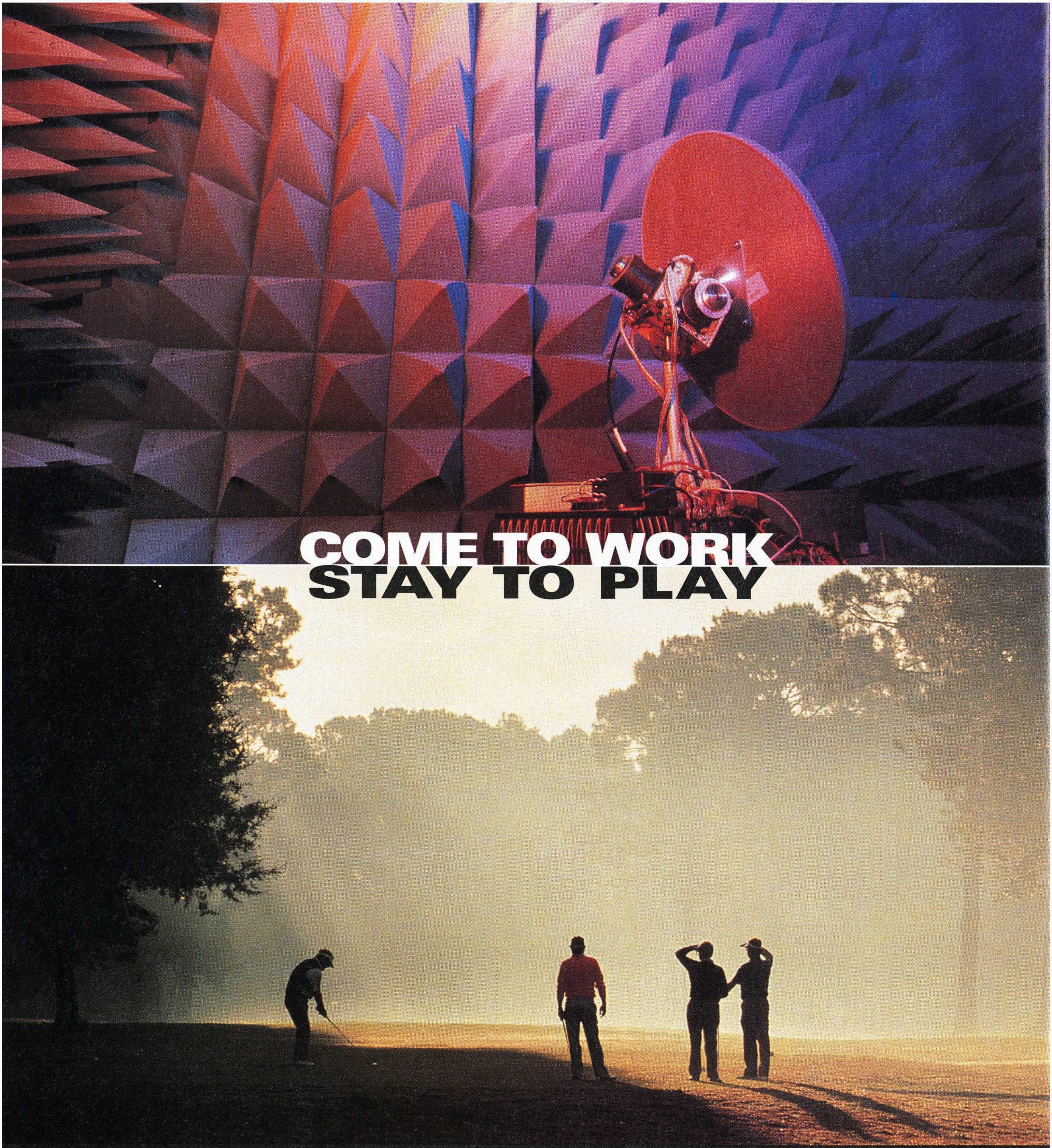
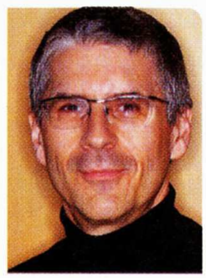

COME TO WORK
STAY TO PLAY

Ch-ch-ch-changes

THIS ISSUE OF *TECHNOLOGY REVIEW* IS UNUSUAL IN SO MANY ways it's hard to know where to begin describing them.

First of all, it's a special issue devoted to "The State of Innovation," following up on the "TR100" issue of a year ago, in which we named 100 young innovators to watch. Rather than repeating ourselves in this Annual Innovation Issue, we've taken a different tack. This time we've picked 10 key areas of emerging technology to watch. The editors of *Technology Review*, in consultation with top technology experts at MIT and elsewhere, predict that these 10 fields will have major impact on our lives in the decade to come. And we've chosen one person in each field who exemplifies the field's promise.

To complement the "TR10," we're offering you a full range of other stories, including two we're particularly proud of: a vision of the future of computing by John Seely Brown, former director of Xerox PARC, the famous Palo Alto research outfit, and the longest interview in some time by Lou Gerstner, IBM's formidable chief executive. I'm especially impressed by Gerstner's skepticism about the "New Economy."



PHOTOGRAPH BY FURNALD/GRAY

This issue is also significant because it marks a milestone in our development: It's the first issue of our new publication cycle. Starting now, *TR* will be published monthly, rather than every other month, as we have been for the past two and a half years. (Strictly speaking, initially we will be published 10 times, with combined issues in January/February—this one—and July/August.) The new frequency will enable us to offer you even broader coverage of the most important emerging technologies.

But the changes we're introducing go far beyond timing. In my last column, I let you know that there would be evolutionary changes in the magazine, and you'll begin to see them here. Part of the evolution is visual. Our new art director, the very talented Eric Mongeon, has polished our graphic design, simplifying, updating and rendering our visual presentation increasingly coherent and consistent.

We also present both new columnists and new departments. The four columnists are Seth Shulman, writing on intellectual property *("Owning the Future," p. 41)*; Michael Hawley, on whether information technology really matters to how we live *("Things That Matter," p. 28)*; Simson Garfinkel, on what's coming next in the computer and networking revolution *("The Net Effect," p. 116)*; and Henry Jenkins, on how technology and culture intersect *("Digital Renaissance," p. 121)*.

In addition, we've created two new monthly departments. "Upstream" *(p. 39)* offers a concise one-page description of an emerging technology we believe bears careful watching over the next couple of years (our first candidate is "spintronics"). What we aim for is the kind of insider's information possessed by the people who knew about the Internet in, say, 1990. "Visualize" *(p. 118)* will provide a graphic, nuts-and-bolts explanation of an important technology (in this issue, DNA chips), showing you just how it works—and why. And, for good measure, we've changed the name of our news department, doffing the old title, "Benchmarks," and substituting one closer to our mandate: "Innovation" *(p. 31)*.

That's a whole lotta new stuff for one issue. And it may take you a while to decide what you think of our new look, feel and content. When you do, let me know. Try: letters@technologyreview.com.

—John Benditt

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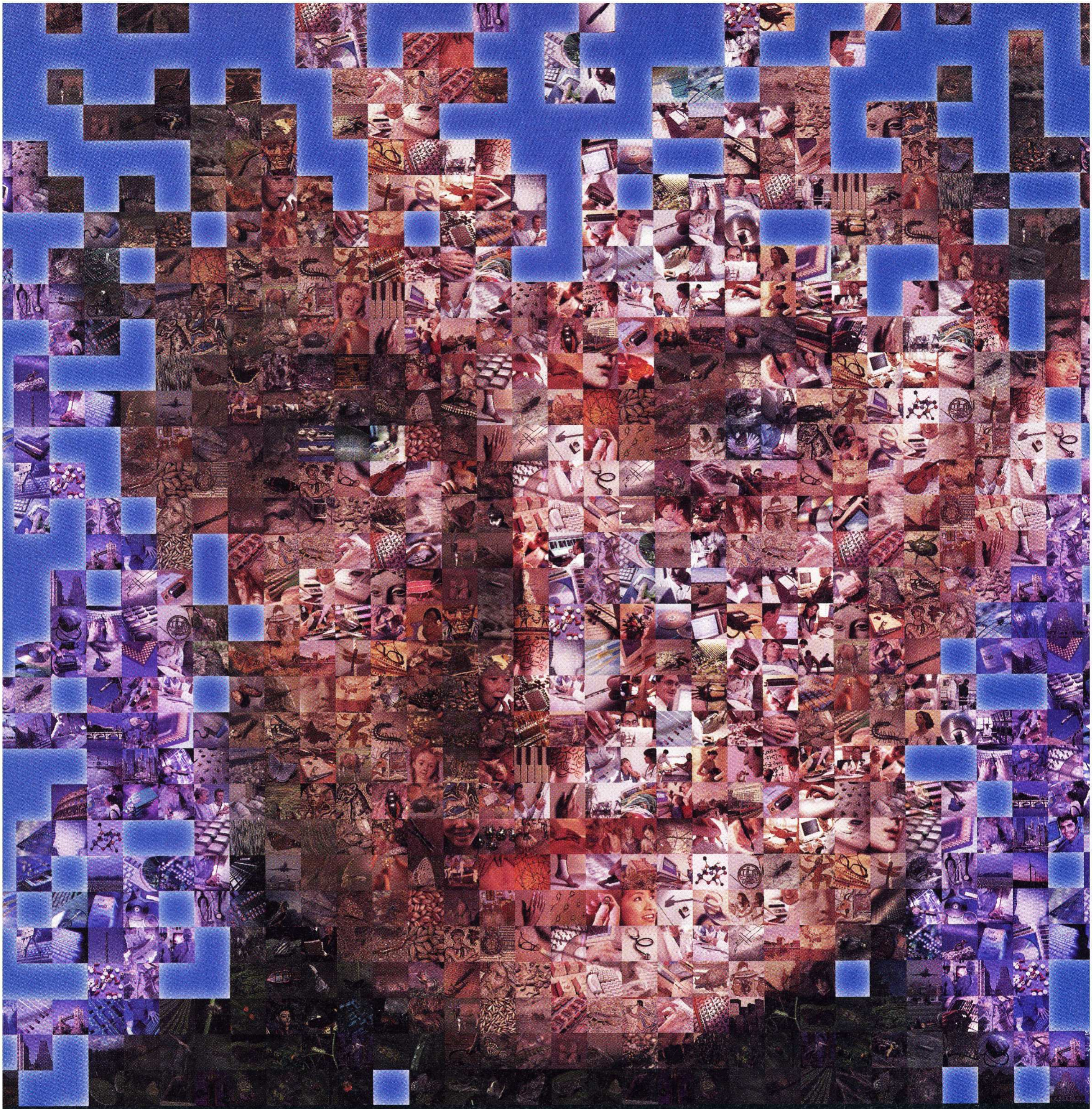


"I firmly believe that OS X has the power to change the computing world as the Macintosh did 16 years ago."

Toppling the Desktop

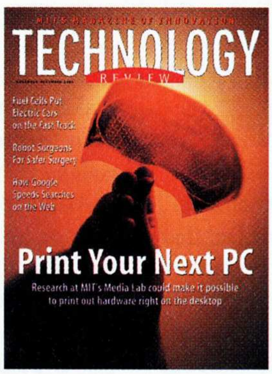
AS A COMPUTER PROFESSIONAL, I appreciate good clean commentary on the latest operating systems offered by articles such as Nick Montfort's review of Macintosh's OS X operating system's Aqua interface ("Toppling the Desktop," *TR* November/December 2000). But as a longtime Mac and UNIX user I feel obliged to clear up some inaccuracies in the article. While it's true that Apple has never shipped a Macintosh with a command line easily accessible by the user, it's definitely not true to say the command line was "never before seen on a Macintosh in the 16-year history of the machine." Various third-party tools provide a command line. And while I wholeheartedly agree that the command line is more powerful for certain tasks, I've found GUI tools on the Mac that accomplish almost every task command lines are touted for, often just as elegantly. Nevertheless, I look forward to the completion of OS X. I firmly believe that it has the power to change the computing world as the Macintosh did 16 years ago.

ROBERT L. KEHRER
Bioinformatics Programmer
Salt Lake City, UT

MONTFORT STATES THAT "AQUA'S desktop is not very desklike." But apart from the fact that the internal hard drives do not appear on the desktop, everything you have been doing on the Mac OS 9 desktop you can do on the Mac OS X desktop as well: copy files to it, create folders, et cetera. What makes this desktop not very desklike? No pencils lying around? Montfort also should not mention the DOS and UNIX command line interfaces together as if they were equal. The DOS command line is extremely limited, frustrating and primitive. People who hated DOS command lines tend to be positively surprised by the power a UNIX command line gives them.

KILIAN MUSTER
Tokyo, Japan

IN HIS REVIEW OF OS X, MONTFORT gives the Dock magnification a thumbs-down but never mentions that this option can be turned on or off and is useful when the Dock has many icons and has to be "shrunk" down. As well, it isn't "borrowed" from the Windows equivalent; it's "borrowed" from the NeXT Dock, which Apple bought the rights to, and by the way, the NeXT Dock was also what Windows "borrowed" its Taskbar from.



GREG JARVIS
Brampton, Ontario
Canada

IS AQUA KILLING THE DESKTOP METAPHOR? I sure hope so! I bought Mac OS X beta to test it out, and these days I rarely boot into classic Mac OS 9, or "Classic" in Mac OS X. Going back to anything else, be it Mac OS 9, Windows 2000 or KDE 2.0, is a horrible experience.

ORJAN LARSSON
Karlskoga, Sweden

Cell Phones: How Scary?

GARY TAUBES, IN "THE CELL-PHONE Scare" (*TR* November/December 2000), would have us believe that concerns over cell-phone radiation are like Elvis sightings and ESP. But plenty of "positive" scientific studies have prompted health concerns. Researchers in Finland, Germany, Switzerland and the United Kingdom have reported that short-term exposures to cell-phone radiation are linked to changes in cognitive function, sleep and blood pressure. Phone users report more headaches—complaints supported by a preliminary study in Sweden and Norway. Taubes never cites the views of any scientists working on this problem.

The "mad cow" fiasco in Britain shows what can happen if we are complacent about uncertain risks. Instead of taking precautionary measures when scientists first raised concerns, the risk to humans was dismissed. The lack of action and false reassurances compromised public health and undermined public confidence in science.

LOUIS SLESIN
Editor, Microwave News
New York, NY

RECENTLY COMPLETED REVIEWS OF international wireless phone standards in Canada, Japan and the United Kingdom unanimously conclude that cell phones adequately protect human health. Several hundred radio frequency (RF) studies in the World Health Organization's research database also support the overwhelming scientific opinion that wireless phones pose no health risks. And the U.S. Food and Drug Administration says "...the available science does not allow us to conclude that mobile phones are absolutely safe, or that they are unsafe. However, the available scientific evidence *does not* demonstrate any adverse health effects associated with the use of mobile phones." [Emphasis in original.]

It is disappointing we haven't seen much of this information in the media. Perhaps we can only assume that good news is not "news."

TOM WHEELER
President and CEO
Cellular Telecommunications Industry Association
Washington, DC

BRAIN TUMORS TAKE MANY YEARS TO develop, and it is now too soon to see a statistically significant increase in cancer among cell-phone users. Taubes' statement, "Over the years, researchers have looked at the effects of electromagnetic radiation at cell-phone-like frequencies...without coming up with any particularly believable evidence that cell

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phones themselves would be harmful," is not true. A study funded by the cell-phone industry in Australia showed that mice chronically exposed to cell-phone radiation were twice as likely to develop cancer. Recent studies using cell-phone frequencies have also reported genetic damage, increased leakage of the blood-brain barrier, changes in cell functions and effects on brain activity in humans. Only research carried out before 1985 was used in setting the current RF radiation exposure guidelines in the United States. Should we be a little concerned?

HENRY LAI
Research Professor of Bioengineering
University of Washington
Seattle, WA

TAUBES' EXCELLENT ARTICLE ON THE cell-phone cancer story comes as a refreshing change from the glut of misinformation and quarter-truths spewing from the media. It did, however, leave out the reason scare tactics are used in the first place. I recently tried to convince the members of my church that we should accept an offer from a cellular provider to place a cell site in the steeple. In the end, the members couldn't listen to reason with the incessant drum of media hype jamming their heads. Whenever the six o'clock news needs a few extra ratings points for sweeps week, the old reliable cellular scare will be trotted out to deliver the eyeballs to the advertisers.

BILL HORNE
Sharon, MA

Taubes responds:
The point of the essay was not to say there is no scientific evidence suggesting cell phones may cause cancer in humans. The point was to examine—using cell phones as the latest, best example—what is likely to happen when that evidence is only suggestive but not definitive or even remotely definitive. That everyone has a different point of view on what constitutes definitive evidence was made clear in the article. That even scientists will differ is also clear. However, as Bacon pointed out, and as I once again feel the need to reiterate: The existence of some positive evidence supporting our preconceived opinions is not sufficient evidence to believe those opinions are right. That evidence could be meaningless, dead wrong or the tip of the iceberg. It is because we tend to overvalue positive evidence that we gamble in casinos, play the lottery, believe in ESP and, all too often, see icebergs where they don't exist.

The Software Chip

THE JURY IS STILL OUT AS TO WHETHER "code-morphing" is the best solution to PC processor design, much less every computing problem in existence, as claimed by Stanford professor John Wharton in Claire Tristram's "The Software Chip" (*TR* November/December 2000). Under different names, code-morphing has been around for a long time, and the problem has always been that mapping one instruction set to another inevitably incurs some loss of performance. Transmeta claims that the loss is less than 20 percent, but initial testing of Crusoe-based notebooks indicates the loss is more than 50 percent on some applications (see http://www.zdnet.co.uk/news/2000/42/ns-18596.html).

Transmeta argues that Crusoe is "fast enough" for most common PC software, which is probably true, but that assertion does not overturn the basic fact that code-morphing wastes a sizable fraction of a processor's native performance. This wastage may be acceptable to achieve PC compatibility, but for a broader range of computing applications, the performance loss from code-morphing simply won't fly.

LINLEY GWENNAP
Principal Analyst
The Linley Group
Mountain View, CA

Fueling Controversy

I FOUND PETER FAIRLEY'S ARTICLE "Fill 'er Up With Hydrogen" (*TR* November/December 2000) illuminating and very exciting as a consumer and as an investor. For a while now, I have been wondering what stage of evolution fuel cell technology was in, why it isn't widely available and what the future holds for fuel cell-powered cars. Fairley's story answered my questions and gave me a comprehensive and satisfying overview of a very complicated subject.

LARRY ARSENAULT
Eugene, OR

IT'S VERY ENCOURAGING TO SEE MAJOR auto manufacturers beginning to think about alternatives to oil, but it seems they are taking the long road. Why, if your ultimate goal is to be able to "fill up with water," would you then spend years and billions to produce onboard refineries for methanol or gas? I guess the CEO of Texaco figures he can sell methanol without changing much at the pump.

JOHN HACKMAN
Belair, MD

FAIRLEY'S ARTICLE IS THE BEST THAT I have read about automotive fuel cell technology for a year or so. I'm a fuel cell fan, but it's difficult for me to find updated insider information like this. It is very well organized and gives the big picture. Many fans and investors need such news to stay up on fuel cells. Fairley's article puts us there.

CURT RICHARDS
Beckley, WV

THE ENORMOUS PROGRESS BY AUTOmakers to power automobiles by generating electricity from hydrogen in fuel cells to reduce output of carbon dioxide and other products of hydrocarbon combustion seems admirable, but production of hydrogen and methanol requires large amounts of energy. Taking into account the carbon dioxide produced at power plants in generating this needed energy, is there any reduction in carbon dioxide?

JAMES M. DAVISON
Chemical Engineer, Retired
Union Carbide
Chemicals and Plastics R&D
South Charleston, WV

I HAVE BEEN INVESTING IN FUEL-CELL stocks for the last year and have read many an article. I thought that yours was the most comprehensive, informative and well rounded of all. Bravo.

CHRIS WILCOX
Berkeley, CA

WHILE I FOUND FAIRLEY'S ARTICLE interesting, I do have a problem with the comment "Remember the Hindenburg?" in his discussion of the direct storage and use of hydrogen aboard a vehicle. Most people in the scientific and technical community now fully accept the fact that the Hindenburg incident did not occur due to hydrogen but due to the flammability of the fabric covering used

and the electrical storm at the time. Hydrogen, when used properly, can be much safer than gasoline or propane, which are widely accepted by the public.

NED T. STETSON
Senior Research Scientist
Energy Conversion Devices
Troy, MI

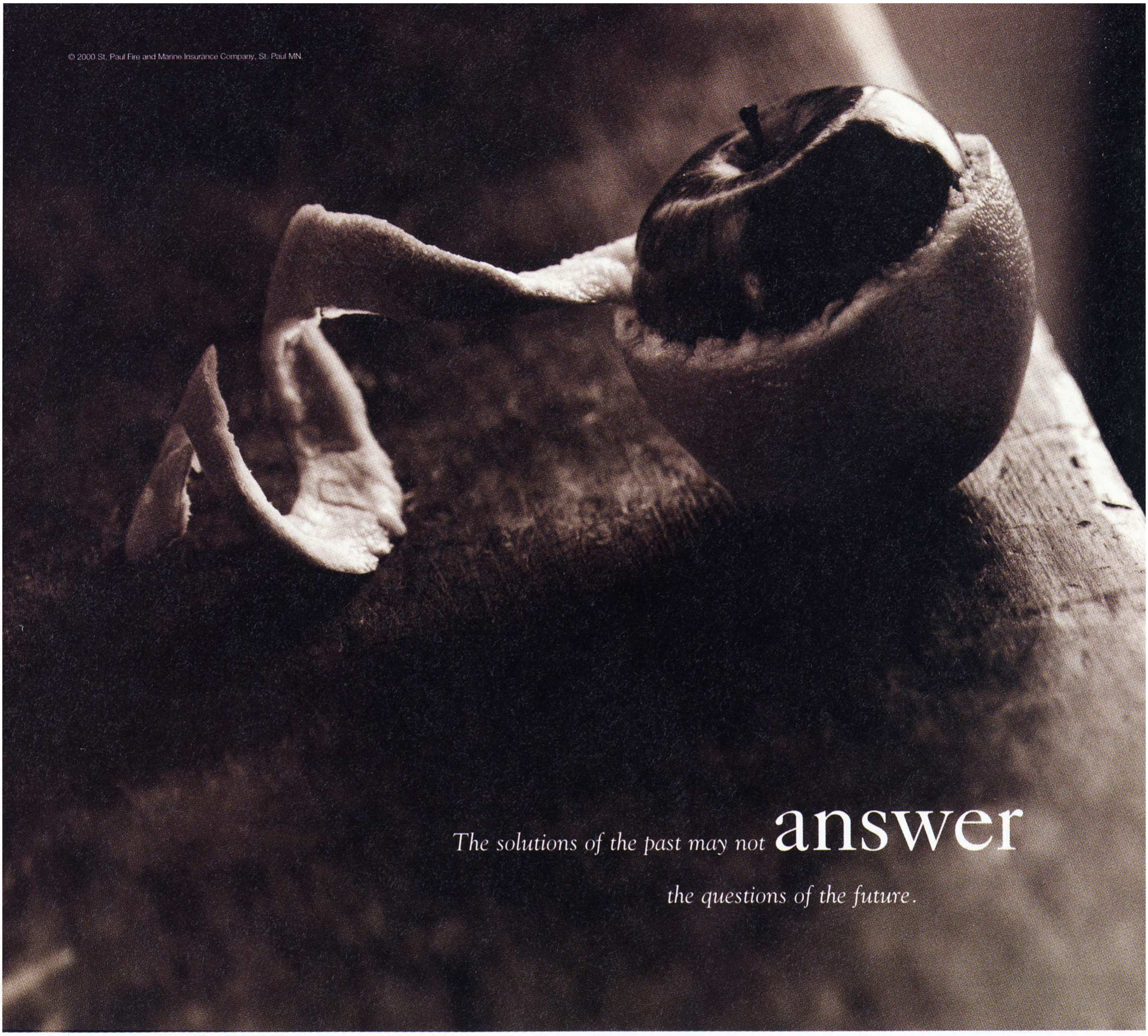
Fairley responds:
Fuel has taken center stage in the race to commercialize fuel cell cars. As I wrote, hydrogen is clearly the ultimate fuel because hydrogen generated via renewable resources such as wind and solar power would rid our transportation system of fossil fuels and their climate-warming byproduct, CO_2. However, running fuel cell cars on hydrogen produced by "cracking" natural gas—the energy-intensive process Davison describes—would still generate 72 percent less CO_2 than an efficient combustion car, according to the David Suzuki Foundation and the Pembina Institute. Their study found that a fuel cell car consuming hydrogen from onboard gasoline or methanol would produce 22 percent and 35 percent less CO_2, respectively, than a conventional car.

While gasoline carries plenty of risks, our society has adapted to it. In contrast, hydrogen enthusiasts such as Hackman and Stetson must convince a risk-averse public to accept these alternative fuels. Even if the Hindenburg's fabric *ignited* the blaze, it is the ensuing fireball that the public remembers. Overcoming that image, as well as thousands of restrictive building codes it spawned, is a prerequisite for public acceptance of hydrogen cars.

My Work Is Whose?

MICHAEL DERTOUZOS' BLANKET REPLY to arguments that Napster is a valuable service is a flat-out "Baloney!" ("Your Work Is Mine!" *TR* November/December 2000). But so is his statement that artists can choose to make their songs freely available. When the band The Offspring recently proposed to offer their new album free on their Web site a month before its commercial release, they were kept from doing so by a threatened breach-of-contract lawsuit by their record label.

RICHARD M. CONLAN
Troy, NY



Is there someone who understands that the past is not a reliable indicator of the future? Someone who believes that constantly evolving industries require innovative, flexible solutions? Is there an insurance company that designs policies specifically tailored to highly specialized, technologically sophisticated companies? Without Question.

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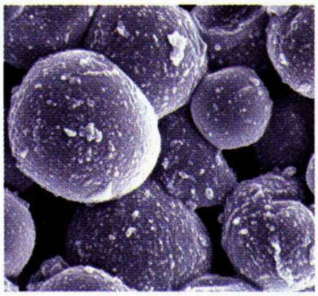
PROTOTYPE

WHAT'S IN THE PIPELINE IN EVERY AREA OF TECHNOLOGY

Denser Disks

Hard-drive capacity has doubled every year recently, a spectacular pace that has let us stuff our computers with text, music and images. But experts predict that without new manufacturing methods, drive capacity will max out in two to three years at around 100 gigabytes. Santa Clara, Calif.-based Intevac, a maker of drive manufacturing systems, is trying to break through that barrier.

Today's systems lay the magnetic grains that make up a hard drive parallel to the disk surface. Orienting the grains perpendicularly instead lets bits be packed perhaps 10 times more closely. But manufacturing difficulties have stymied development of this 20-year-old idea. A machine for producing these perpendicular media must deposit 40 to 80 alternating layers of magnetic material, each only a few tenths of a nanometer thick. Intevac is working to develop just such a system. If the project succeeds, says Terry Bluck, Intevac's vice president of equipment engineering, 500-gigabyte drives could be on the market in five years for \$100 to \$200—the price of a 20-gigabyte drive today.



FRAUNHOFER INSTITUTE

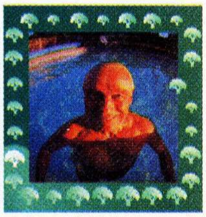
Fragrant microcapsules warn of wear.

The Smell of Trouble

Industrial tools must be monitored daily for wear and tear—a labor-intensive process that sacrifices production time. A new surface coating developed at the Fraunhofer Institute for Surface Engineering and Thin Films, in Brunswick, Germany, promises a more efficient way to smell trouble.

The coating, embedded with fragrance-filled microcapsules, is applied to tools and machinery. As a protective top layer wears thin, the capsules are broken and the fragrance is released. For household tools, any concentrated fragrances, such as perfumes, can be used and detected by the human nose. For industrial machinery, other indicators, such as gases, can be encapsulated. When released, they can be detected by a sensor that triggers an alarm. The researchers aim to have the coatings commercially available in Europe within about a year.

Digital Family



GEORGIA TECH/PHOTODISC, INC., ©1999

Icons show grandpa's okay.

It isn't easy to check up on one's elderly parents from afar, but perhaps technology can offer a partial solution. Researchers at Georgia Tech have developed an Internet-based "digital family portrait" designed for families to hang on the wall and receive daily information on their parents' well-being. Sensors at the parents' home record how much they climb stairs or move around. A computer compiles the information and sends it over the Internet to the digital portrait—a flat-panel display mounted on a wooden frame. Icons arrayed around the photo change in size to indicate how active the parent is on a given day. The folks who are monitored can choose the information they want transmitted. "We're not building a granny-cam," says project leader Elizabeth Mynatt. "Nobody really wants that." While commercialization is possible within a year, Mynatt's next project is to make frames for monitoring health and socialization.

Humanizing the Pig

Recent studies have shown that pigs could donate hearts and kidneys for people. But livers, which rely on enzymes specific to each species, are more difficult. Now comes a promising new approach: partly humanize the pig's liver. Researchers at Ximerex in Omaha, Neb., infused human liver cells into fetal pigs and watched the cells produce human liver enzymes. But with no room in the pigs' livers, the human cells ended up in the spleen. To solve this space problem, Ximerex is developing genetically modified pigs programmed to kill off 20 to 80 percent of their own liver cells. The next step will be to transfer the pigs' immune cells to the patient to build up a tolerance of the hybrid organ. Working with the University of Nebraska, Ximerex hopes to begin human trials in 2005, says President William Beschorner.

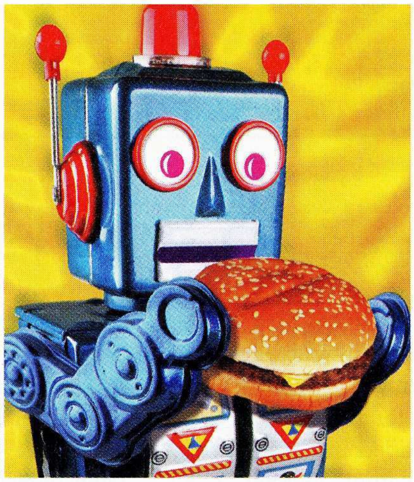
THE IMAGE BANK

Toothsome Plastic

Heat-resistant plastics are invaluable in applications such as high-tech military airplane engines, where low weight is crucial. But even strengthened with graphite fibers, current versions tend to shatter when hit. A new composite plastic from an unlikely origin could change all that.

Trying to improve the wear resistance of dental fillings, Ohio State materials scientist John Lannutti and dental researcher Robert Seghi forced a plastic through microscopic pores in tiny silica particles. Lannutti found that the process not only produced a wear-resistant filling but also improved resistance to impact. So he combined the silica with a heat-resistant plastic used in airplane engines, creating a material that Lannutti says should fail "gracefully" rather than "catastrophically." BFGoodrich may use the silica-plastic composite in aircraft engines within a year, and Ford Motor has expressed interest in using the material to create lighter auto engines.

Gastrobot



VITO ALUJA; ROBOT COURTESY OF TINTOYS.COM

The "gastrobot" has arrived: the world's first robot that eats and digests to generate its own power and that may eventually produce robo-poop. The hungry robot, built at the University of South Florida in Tampa and dubbed Gastronome, is one meter long and rolls on 12 wheels. Gastronome is powered by a microbial fuel cell filled with *E. coli* bacteria. So far it only ingests sugar; as the bacteria break down glucose molecules, electrons are released and captured to charge a battery, which powers the motor. The contraption could run on vegetation—or meat, for maximum energy—but would eventually become constipated: The complicated process of waste elimination hasn't been perfected. Inventor Stuart Wilkinson, an associate professor of mechanical engineering, says one eventual commercial use could be a robotic lawn mower that eats the clippings for power.

Laying Picture Tiles

Those in pursuit of the ultimate home theater face a dilemma in choosing a large-screen display. Traditional cathode-ray tube (CRT) sets are bulky, and two alternatives—plasma displays and rear-projection screens—look washed out. Liquid crystal display (LCD) screens have not yet been produced at sizes larger than 30 inches (about 75 centimeters). A joint venture between Philips Flat Display Systems in San Jose, Calif., and Endicott, N.Y.-based Rainbow Displays will soon provide another option: "tiled" LCD screens. Using a row of three LCD panels, Rainbow and Philips have created a 95-centimeter screen with a wide viewing angle and resolutions comparable to those of today's TVs. Philips and Rainbow Systems will initially market the screens as corporate signage for about $10,000—less than half the cost of the largest single-panel LCDs. By year's end, they hope to sell the screens to consumers for $5,000 to $7,000.

Cool Chips

As computer chips get smaller and faster, they become little electronic furnaces—and a lot of research goes into finding better ways to carry away the heat so the chip can do its work without melting. One new solution from the University of Pennsylvania: carbon nanotubes, each only one ten-thousandth the width of a human hair. Studied since their discovery in 1991 for their strength and electrical properties, nanotubes could be the world's best heat conductors as well. Materials scientist John Fischer and physicist Alan Johnson measured the speed of sound waves traveling down the tubes as an indirect gauge of heat propagation and found it to be about 10,000 meters per second. Contrary to expectations, connections between tubes in a bundle did not slow the waves. This suggests that single tubes or bundles of aligned tubes could be used to carry heat away from computer chips. The University of Pennsylvania is seeking to license the application to device makers such as Advanced Micro Devices and Intel.

Teddy Goes High Tech

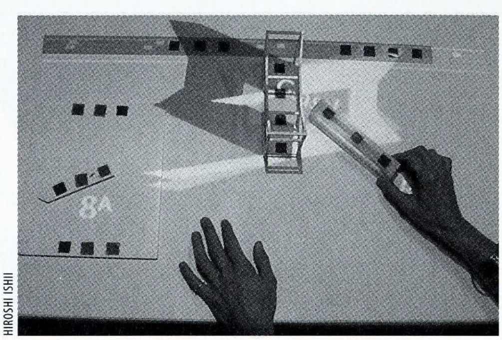
CGI-DARMSTADT

The major conference of the year is in Australia, but the boss won't spring for tickets. How to be in two places at once? Enter Telebuddy—a high-tech teddy bear that lends its eyes, ears and voice to remote users via the Web. The brainchild of researchers at two German organizations—the Computer Graphics Center in Darmstadt and the Fraunhofer Institute for Computer Graphics in Rostock—Telebuddy's nervous system includes a camera, a microphone, speakers and robotics, all linked via radio to a local computer connected to the Web. Remote users can see and hear what Telebuddy does as the person who carries it in a backpack ambles through the exhibit halls and chats with passersby. The office-bound person can also type in questions, which Telebuddy translates into synthetic speech to provide a live chat interface. Telebuddy attended its first conference last July, and its developers are exploring entertainment uses.

Simulated Cityscape

You're an urban planner, looking at a tabletop model of a city. You would like to know what the impact would be if a proposed new building were moved to the left, so you shift it slightly. A digital shadow appears from the base of the building, a high-speed wind tunnel is generated and the reflection off the glass building blinds motorists driving by—evidence that perhaps the change wouldn't be such a good idea after all.

Developed under the direction of Hiroshi Ishii at MIT's Media Lab, this urban simulation uses a specially designed lightbulb with a built-in camera and projector to track the position of buildings in a model. The camera recognizes the structures using an optical tagging system; small colored dots encode the object's dimensions. When a structure is moved, the system displays the resulting shadows and wind patterns on the model's surface. Developers in Boston and Washington, D.C. have already expressed interest in using the system for their construction projects.



HIROSHI ISHII

Virtual shadows help design urban spaces.

Khmer Kids Link to the Future

BRRR! NOT JUST ANOTHER frosty January in Cambridge, not just a new year, but 010101: the real dawn of the new millennium. But it feels like a digital winter in more ways than that. The Internet bubble deflated, leaving not only pissy investors and a chill on Wall Street but a generation of hackers frozen like mastodons in the Microsoft ice age, and a lot of decent people wondering: What good is this computer stuff anyway? Sufficiently advanced technology may be indistinguishable from magic, but is it really making life more worth living? Where's the beef?

Even at the MIT Media Lab, which has been ground zero for blast after digital blast, teams are scrambling to pioneer a post-computer society, exploring implications for life in the numinous high-tech beyond, sometime after the Internet. A few years ago, to teethe on this, we launched an effort called Things That Think (TTT), our cute name for a research thrust to explore embedded intelligence very broadly. What might happen when commonplace objects, like shoes or underwear or furniture or toys, begin to contain more sensory and computer power than we can currently predict, and when innate, wireless nets fluidly link them to the rest of the planet's infinitely scaling information systems? Surely, thinking machinery will infest heretofore inanimate things. What then? The implications are fantastic and profound.

TTT felt like a big bang when we launched it. We put on our sunglasses with embedded holodisplays, ready for a bright future. After all, we were blazing trails into a networked world that would stretch far beyond today's Tinkertoy Internet. It was so obvious: The computer revolution hadn't even begun yet. But after just a few years, folks (observers and researchers alike) became blasé. Being digital was for old farts. As the giddiness faded, we tried being more outrageous: How about edible computing? Quantum machinery? A smart coffee cup? Teleportation? And visitors would say, "Oh." It was as if every whizzy thing that could be dreamed could be built. Science fiction was just an implementation detail. What's a poor inventor to do? Retire to a life of venture capital?

As the digital industries grow out of their adolescence, people are beginning to question where these technologies are really taking us. So when an old lab's research themes fade and new ones emerge, folks pay attention. And at the Media Lab, the freshest aims involve domains such as art and human expression, creative societies in developing nations, expeditionary and ecological field efforts, and Media

MICHAEL HAWLEY

Image of the new world: Khmer kids at Angkor come face to face with themselves in the mirror of a digital video camera.

Labs in other countries as an ongoing way to explore creative technology in indigenous contexts—bold and humane efforts that take computing and communication and any other sort of imaginative technology utterly for granted, like paper or duct tape.

To me, some of the most interesting avenues involve the deployment of powerful technologies in communities that are furthest from being overtly ready, in the hands of people who are passionate and starving to put it to use. One of the world's best examples is Cambodia.

The first time I visited, about five years ago, Cambodia was a nation of about 10 million people with perhaps 10,000 telephones. You could count the cars in Phnom Penh. Most taxis were scooters (for 50 cents, you could ride almost anywhere). Few roads were paved. Electricity was sporadic. The temples at Angkor had recently reopened, though few visitors made the pilgrimage. Pockets of Khmer Rouge troops were still at large in the Elephant Mountains to the north, as was Pol Pot, so the remote temples were off limits. I saw a horrifying number of amputees.

My most vivid memory, though, is of the children: There were wonderful kids running and playing everywhere, bubbling over with energy. It was like seeing the green baby plants that grow back after a forest fire. Walk through the temple ruins at Angkor, and you were never alone: A swarm of kids surrounded you, first begging for handouts but quickly giving way to laughter and games. They seemed to be able to chatter in most of the tourist languages and make lightning calculations of foreign currency values.

At the time, I wondered how technology might take root there. Cell phones were a natural; developing regions often leapfrog to next-generation technologies. But with such a lack of infrastructure, how would computers find a useful role? The answer turned out to be by leapfrogging to the next generation of people.

Today, for U.S. $14,000 you can build an elementary school in rural Cambodia. You can even name it for someone you love. Click on www.cambodiaschools.com and build one. Last year, I saved my money and built a school for my mom; it was the nicest Christmas present she had ever received. And what happens to your donation is extraordinary.

By spreading computer literacy, Cambodian orphans are not just bootstrapping technology—they are bootstrapping the culture and self-esteem of the community around them.

Your $14,000 is matched by $12,000 from the World Bank. And $2,000 of it is kept for teachers' salaries (in order to import a new breed of teachers). So for $24,000 net, a three- to five-room elementary school is built in a rural village. But for an extra $1,700, the school gets a solar roof to power its computers (ah, there's the technology). Apple Japan and others have been donating machinery to these causes.

Now, in these schools, there is no segregation by race, age, intelligence or anything else, which is undoubtedly a healthier way to learn than the factory format used in most Western countries. There's certainly no busing. And as quickly as we can manage it, the schools will be online: remote village schools, jacked into the world's online knowledge. You'll find Khmer kids tuning in to online lectures from great university professors. It's already happening. There's only one problem: Who can help these schools bootstrap, and bring them up to speed with computer skills? The amazing answer turns out to be—orphans.

One of the heartbreaking consequences of the Pol Pot regime is the number of orphans. The Future Light Orphanage on the outskirts of Phnom Penh is a computer learning center for orphaned kids (www.camnet.com.kh/future.light). The orphanage has been equipped with a large number of computers (including machines no longer needed at MIT). In just a few years, some of Cambodia's savviest computer experts have grown up there.

So when it came time to bootstrap computer-based teaching in rural villages like Robib (see www.villageleap.com), the orphaned kids were invited to help (with permission of the minister for education). Like an MIS SWAT team, the kids set up machines, got e-mail working so they could stay in touch with their pals back home, and hacked at ways to transmit Khmer, their native language (Microsoft Outlook chokes on Khmer) instead of broken English. Today, this network helps Robib villagers sell silk weavings in a new worldwide market.

When you ask Cambodian kids what they want to be when they grow up, the answer used to be "a truck driver." Or a cook, or a waiter in one of the fancy new hotels. But ask the kids at the orphanage, and the answer is, "I want to be a computer pioneer." And ask the orphans after they've gone into a village to help the schools bootstrap, and they say, "I want to be a teacher." They are not just bootstrapping the technology; they are bootstrapping the culture, and the self-esteem of the community around them.

By January, there will be between 30 and 50 new schools in Cambodia. Thanks to this new form of networked microphilanthropy, you can watch online, brick by brick, as the school you helped found comes together. You will receive the very first e-mail messages as kids come online. I plan to visit the schools myself in February, with my mother. Mom will help dedicate the Dixon Learning Center. It's the best Christmas present ever: a cure for the digital winter, and a reconnection to things that matter. ◊

Michael Hawley is the Alex W. Dreyfoos Assistant Professor of Media Technology at the MIT Media Lab.

PHOTOGRAPH BY FURNALD/GRAY

TOYOTA HYBRID SYSTEM

MPG 52/45 F E 566mi CO_2 1/2 NO_X 1/10

all figures based on EPA estimates — city/hwy mileage — actual results may vary — compared to conventional gasoline engines

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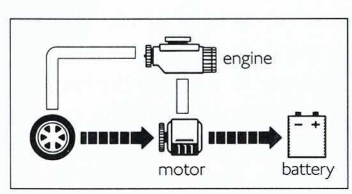

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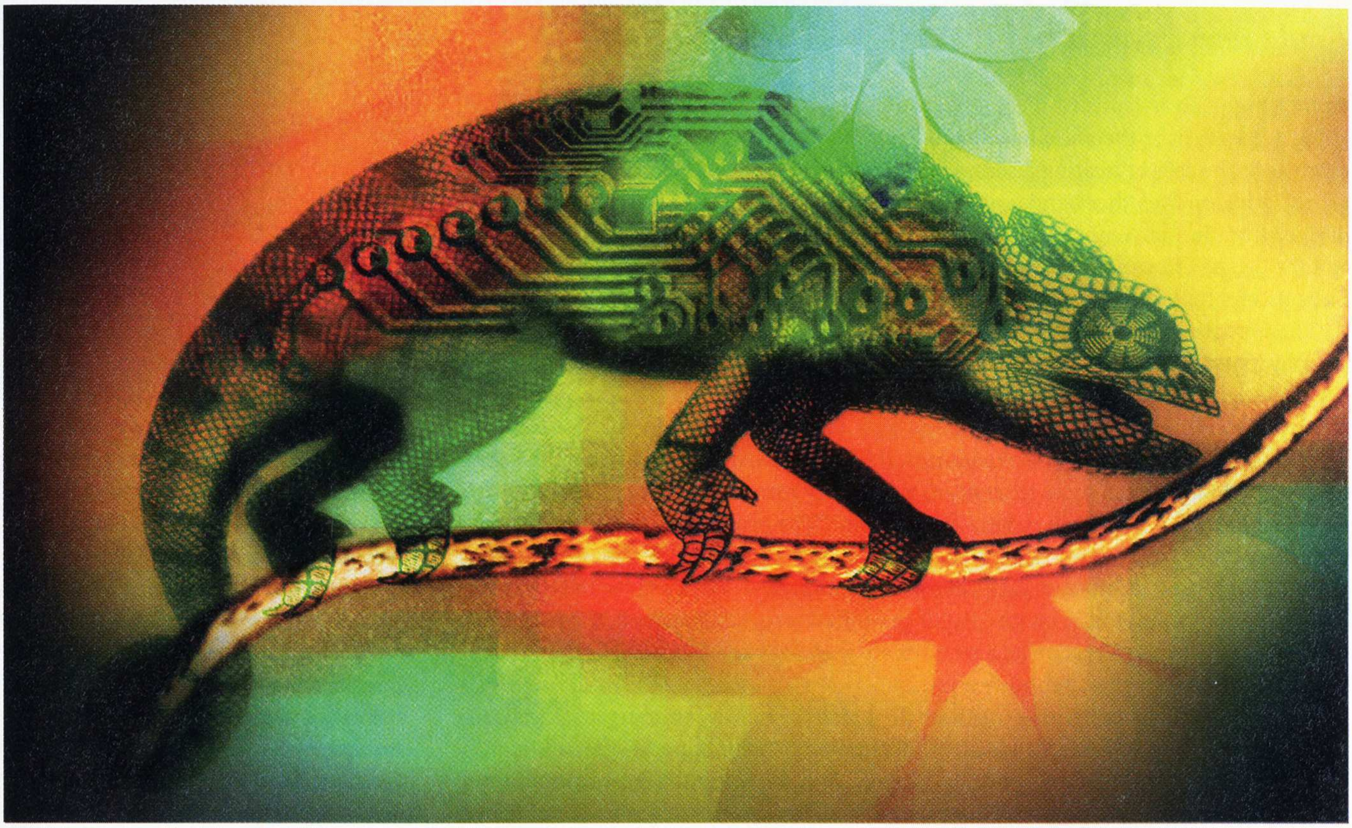


BRIAN STAUFFER

Chameleon Chips

Hardware that can reconfigure itself on the fly could give wireless devices more power

WIRELESS | You've seen the commercials. Soon you'll be doing business on the beach, complete with audioconferencing and instantaneous access to the latest sales data from the office. What this vision of a wireless future disregards, though, is that high-end portable devices have a voracious need for power because each application requires its own silicon chip. Maybe wireless computing has a future, but it's only going to last as long as your batteries do.

Silicon Valley-based QuickSilver Technology, one of many startups working on the problem, has found a way to drastically cut power requirements by making a single silicon chip that can reconfigure itself on the fly to understand different wireless signals. Developed in partnership with BellSouth and scheduled for midyear release, QuickSilver's first chip will be able to decode incompatible cell-phone standards so that a user can access different phone networks instead of just one. Eventually the company expects to have chips that can run multiple applications, switching from audio to video to text processing—all on the juice of a cell phone. "What we're really doing is building a container," says Paul Master, vice president of technology at QuickSilver. "The value is the software you pour into it."

The QuickSilver chip includes a programmable logic "fabric," an array of logic gates that can understand software signals and reprogram itself for different operations. When a chip receives, say, a specific cellular-phone signal, it calls instructions to support that signal's protocol from its memory, loads the appropriate architecture into the reconfigurable portion of the chip and executes the operation. When it receives a different type of signal, it reconfigures itself once more and repeats the process. By comparison, a device that used a different piece of silicon for each operation would drain a battery in no time—that's why it's currently difficult to play MP3 files on your cell phone.

If QuickSilver does deliver, then yet another important piece of the wireless computing puzzle will have fallen into place. "They're trying to do something that hasn't been done before, and it's not clear they'll succeed," says Nick Tredennick, editor of *Dynamic Silicon*, a newsletter that covers dynamic logic devices. "But of course, you could say that about all great ideas." **—Claire Tristram**

Sourcing Stem Cells

Could new research end the embryo debate?

BIOTECH | Ever since human embryonic stem (ES) cells were first isolated in 1998, a debate over their use has raged. Proponents of ES cell research say that the promise of the cells in treating diseases ranging from heart failure to paralysis is invaluable. Critics, on the other hand, argue that the ethical cost of using ES cells, which are derived from human embryos, is too high. Scotland-based PPL Therapeutics hopes to end the debate once and for all by developing an unlimited source of stem cells—without ever creating or destroying an embryo.

The potential of ES cells to treat a spectrum of diseases lies in the fact that the cells are "pluripotent," meaning they can form any tissue in the adult body *(see "Biotech Taboo,"* TR *July/August 1998)*. In October, PPL's labs in Blacksburg, Va., won a $1.9 million grant from the National Institute of Standards and Technology (NIST) for research on reprogramming adult cells to be pluripotent. If PPL succeeds, it will free researchers and eventually doctors from their reliance on a relatively rare commodity: aborted fetuses and embryos left over from in vitro fertilization. "The benefits are ethical on the one hand, and they could be practical on the other," says Ron James, PPL's chief executive.

PPL's three-year grant from NIST allows the company to work only with cells from livestock and nonhuman primates. But if the initial research goes well, the company could privately fund efforts toward its ultimate goal: human-derived cells that can be used in a number of therapeutic applications.

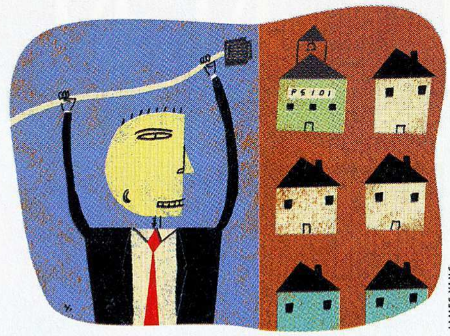
When it comes to explaining just how they plan on reprogramming adult cells to behave like ES cells, PPL executives are understandably tight-lipped—after all, such a trick is the Holy Grail of developmental biology. And the company faces competition not only from those working with ES cells, but also from a growing number of firms that are focusing instead on isolating stem cells from adult tissues such as blood and brain *(see table below)*.

Because they have traveled further on a pathway of differentiation than an embryo's cells have, such tissue-specific stem cells are believed by many to have more limited potential than ES cells or those that PPL hopes to create. Some researchers, however, are beginning to argue that these limitations would actually make tissue-specific stem cells safer than their pluripotent counterparts. University of Pennsylvania bioethicist Glenn McGee is one of the most vocal critics on this point: "The emerging truth in the lab is that pluripotent stem cells are hard to rein in. The potential that they would explode into a cancerous mass after a stem cell transplant might turn out to be the Pandora's box of stem cell research."

So far, the ethical debate on deriving stem cells from embryos has obscured such vital scientific questions. Perhaps advances like PPL's will, at the very least, make discussion of these issues possible. **—Erika Jonietz**

Companies Researching Adult Stem Cells

COMPANY	LOCATION	STEM CELL TYPE
Aastrom Biosciences	Ann Arbor, Mich.	Blood
Neuronyx	Malvern, Pa.	Nerve
Nexell Therapeutics	Irvine, Calif.	Blood
Osiris Therapeutics	Baltimore, Md.	Connective tissue
StemCells	Sunnyvale, Calif.	Nerve, blood



JAMES YANG

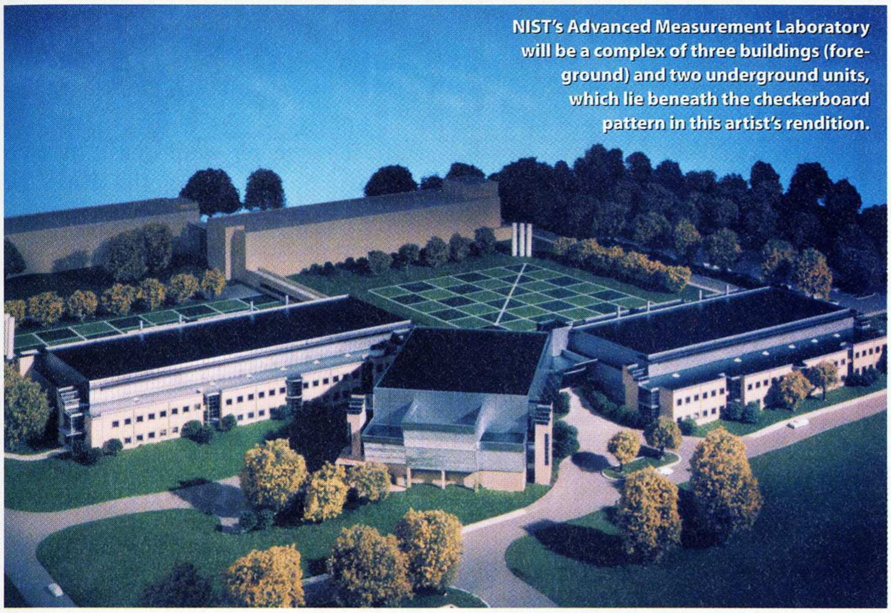
Fiber to School

BROADBAND | **Recognizing the Internet's educational potential, schools have scrambled to get wired. Now a Canadian group has come up with a clever and affordable strategy to bring broadband Internet connections to whole school districts. Eventually, the initiative could help extend high-speed fiber-optic links to homes as well.**

The scheme is the brainchild of Bill St. Arnaud, senior director for network projects at an Ottawa-based Internet consortium of companies and universities called CANARIE. The key, says St. Arnaud, lies in using high-speed versions of the Ethernet format originally developed for local-area networks to transmit signals over fiber from a central location to each school. That way, the costly equipment used to convert broadband transmissions from the Internet into a form suitable for local computers is required only at one site; from there fibers carry the Ethernet signal to inexpensive hubs in each school.

Using Ethernet, one district linked 70 schools and a dozen other buildings. The system cost almost $1 million, but the district now shares ownership of it with four local companies who paid half the bill for a cut of the network capacity. Had the district instead used digital subscriber lines, for example, it would have spent close to $1 million for just three years of service.

Soon, schools or other buildings could be jumping-off points for affordable neighborhood broadband access. Indeed, a handful of companies, including World Wide Packets and Western Integrated Networks, are adapting the CANARIE approach to extend high-speed Ethernet services all the way to homes over optical fibers. **—Jeff Hecht**



NIST's Advanced Measurement Laboratory will be a complex of three buildings (foreground) and two underground units, which lie beneath the checkerboard pattern in this artist's rendition.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Bad Vibrations

NIST hopes to stifle the tremors that ruin experiments

ARCHITECTURE | The National Institute of Standards and Technology is famous for always taking the art and science of measurement to the next decimal place. Now, tons of dirt are moving at NIST's headquarters in Gaithersburg, Md., to make way for a world-class laboratory hosting some of the most tightly controlled environments on the planet.

The argument for the Advanced Measurement Laboratory (AML) is simple: NIST's buildings, which were constructed nearly 40 years ago when integrated circuits were new, can't handle ever more demanding measurement research. "We have to start over," says physicist Robert Celotta, a NIST veteran looking toward an era of nanoscience and nanoengineering. Already, some of NIST's instruments are so sensitive that spark plugs firing almost a kilometer away disturb them.

How annoying can that be to researchers who measure quadrillionth-of-a-second laser pulses and interatomic distances on semiconductor crystals? NIST Director Raymond Kammer waves his hands as though he were steadying himself on a shaky subway. "From the perspective of an atom, this is what it's like here," he says. Besides vibration, airborne particles and fluctuating temperature and humidity also are showstoppers.

This past September, NIST announced it had signed a $174 million construction contract; work was slated to begin before the end of 2000. If the AML lives up to its design specs when its doors open in 2004, its steadiest laboratory surfaces will move less than a picometer (a trillionth of a meter) per second. That's "a fraction of an atomic width," says Celotta. In many of the AML's underground laboratories, floors suspended on arrays of computer-controlled and pneumatically adjustable air springs will quell low-frequency vibrations. Atop these, vibration-isolation tables with their own suspensions will dampen higher-frequency tremors. And some instruments will rely on additional thermal, magnetic and electromagnetic shields to combat even the subtlest forces.

To eradicate particles, the air in the AML's cleanest spaces will change over 300 times per hour, flowing through ceilings made almost entirely of filters. Most of the AML is expected to average about 30 particles per liter of air, down from the 70,000 to 100,000 particle counts in NIST's general-purpose labs. To reduce temperature fluctuations to as low as one-hundredth of a degree Celsius and humidity variations down to 1 percent, arrays of precise thermometers and humidity sensors in each laboratory will feed data into computers that control the AML's heaters and coolers.

Celotta, for one, looks forward to installing his new microscope at the AML, and examining surfaces atom by atom, in perfect stillness. **—Ivan Amato**

Killing Sparks

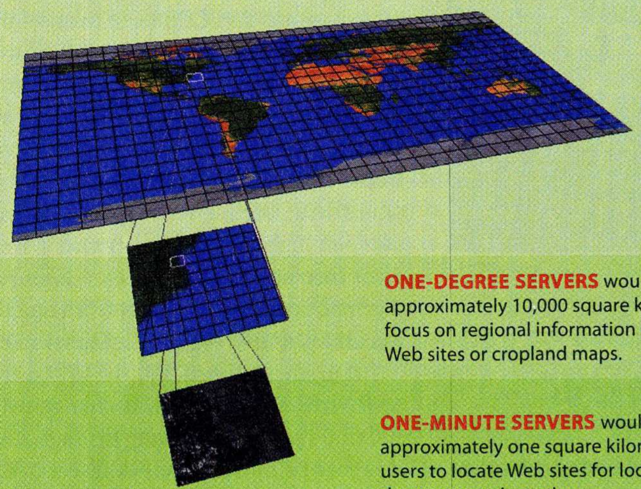
FPG INTERNATIONAL

AIR SAFETY | An airplane's nervous system is its electrical wiring, and on many older aircraft, nerves are a bit raw. The polymer sheaths covering wires are subjected to "everything from deicing salts to Coca-Cola, airborne particles, vibration and rubbing against sharp corners," says Northwestern University materials scientist Thomas Mason. Cracks, holes and thin spots in the sheaths can cause breakdowns or disaster: Investigators suspect a faulty fuel-gauge wire caused the 1996 explosion of TWA Flight 800.

Wires are for the most part inspected visually, but that's difficult when they run through inaccessible parts of the plane. And pulling brittle wires out to look at them can actually damage them more. But Mason and other researchers in a three-year project at Northwestern aim to engineer a noninvasive wiring test by using a technique called impedance/dielectric spectroscopy, which measures the response of a wire to a range of frequencies of alternating current. Comparing the impedance response, or "signature," of an older wire to that of a fresh, new wire could reveal the kind of damage—abrasion, holes or chemical assault—to the wire's polymer sheathing, as well as the degree of degradation and perhaps even its location along the wire. That's the hope, anyway. L. Catherine Brinson, leader of the Federal Aviation Administration-funded project, estimates a working prototype is at least five years off. —Deborah Kreuze

Think Globally, Search Locally

In the .geo system, the globe would be carved by latitude and longitude into "cells" of three different sizes. Dedicated servers assigned to each cell would hold the geographical data registered to company and organization Web sites, maps and other information about that area. Search engines could direct queries to one type of server, depending on what the Web user was looking for.



SOURCE: MARTIN REDDY, SRI INTERNATIONAL

Where in the World?

A new scheme unites the Internet and geography

INTERNET | The Web can be a world unto itself, but there are many times when it would be nice if you could understand its correspondence to actual geography. Say you want the Web sites of all the museums in Boston within a few miles of your apartment, or directions to the shoe repair store nearest to where you're standing with your Web-enabled cell phone. Some search engines and online directories can provide the information, but the power and accuracy of your search depend on how many sites that search engine has indexed, or how many businesses have registered their addresses with the directory.

What if, instead, there was a consistent way for all Internet-navigation tools to keep track of businesses' and organizations' real-world locations, as well as their Internet addresses? That's just what a new Internet architecture proposed by Menlo Park, Calif.'s SRI International aims to do.

Last fall, the Internet Corporation for Assigned Names and Numbers (ICANN), a nonprofit corporation responsible for the assignment of Internet domain names, considered a new series of proposed top-level domains (TLDs) to supplant the now-crowded original ones: .com, .org and .net. Among the more than 200 TLDs suggested by companies from around the world was SRI's proposed .geo—a central component of the research outfit's plan for a new geographic Internet infrastructure.

Here's how the .geo system would work: When a store first registered its domain name, say www.GoldenGateSuits.com, it would also have the opportunity to register its latitude, longitude and a description of the store's Web site with one of several companies called "GeoRegistries." The GeoRegistry—call it Acme in this case—would store the information on a server dedicated to the specific geographic area that encompasses the suit store. That server would have its own domain name, along the lines of "acme.28w49n.2w7n.120w30n.geo." The first part of the address (acme) indicates which GeoRegistry owns the server and the lengthy middle part of the address specifies the geographical region covered by that computer.

An Internet user, however, would never have to see this rather unwieldy name. He could simply go to any .geo-enabled search engine, type in the key words "men's clothing store," and in a separate box, "Pacific Heights, San Francisco." The search engine would then translate the neighborhood and city name into a geographic location, contact all the GeoRegistry servers responsible for that area, and find all the Web sites registered to men's clothing stores in the Pacific Heights area of San Francisco.

One of the forces behind SRI's proposal was the desire to put control in the hands of the businesses who put their Web sites up on the Internet and hope to be found, instead of in the hands of intermediaries such as search engines or online business directories and reviews.

"All of these sites give you a very narrow view of what's in the area you're interested in," says Yvan Leclerc, director of the .geo initiative at SRI. And with the rise in demand for location-based information services for wireless devices, technologists are starting to grapple with the issue of how to organize and store geographical information in a systematic way that everyone can follow.

As *TR* went to press, ICANN announced its list of approved TLDs, which didn't include .geo. ICANN emphasized, though, that applicants could resubmit their proposals. Already, .geo has raised eyebrows in the Internet community. Some have criticized it for adding another layer of complexity to the Web. Others have questioned whether SRI would have a monopoly over the naming system. Still, "the basic idea is a very intriguing one," says Joseph Ferreira, professor of urban studies at MIT and an expert in geographic information systems. "Sooner or later something like this is going to catch on. If not a .geo, then some other scheme." **—Alexandra Stikeman**

Drug Delivery With Muscle

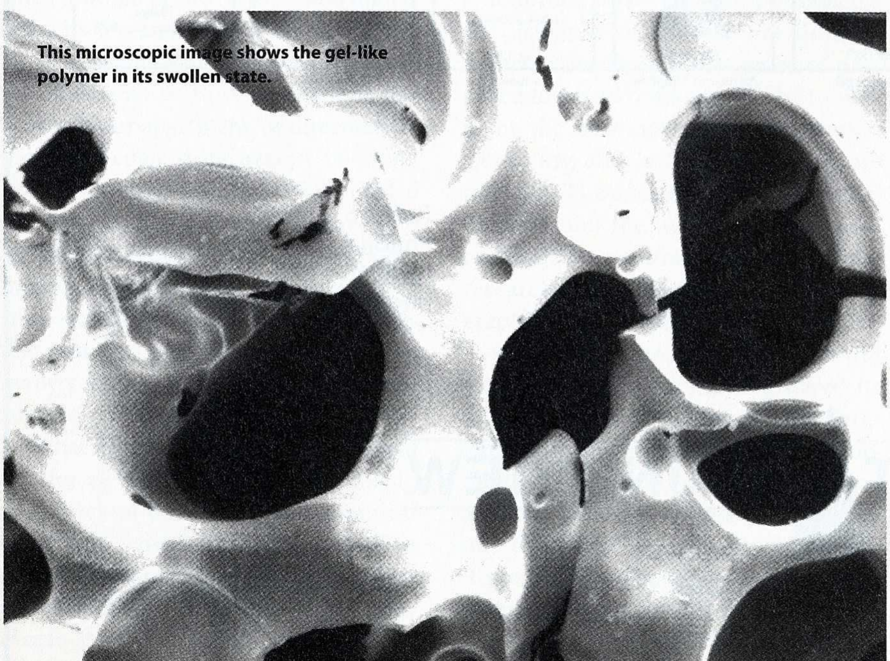
Artificial muscles release medications with precision

MEDICINE | Pills and injections serve us well, but for a patient with a chronic illness like diabetes or heart disease, they are less than perfect. Dosages don't always match the body's fluctuating needs, and it's easy to forget to take a pill. But what if doctors could implant a small capsule under your skin that could detect, say, changes in blood sugar levels or some heart disease-related molecule and then release the exact amount of medication needed to keep your illness in check? That's the idea behind a new generation of "smart" drug-delivery devices being worked on by a number of research labs. One of the challenges in making these devices practical is building valves capable of releasing precise amounts of medications from the device's reservoir.

To overcome that hurdle, Ohio State University's Marc Madou, professor of materials science and engineering, is using capsules equipped with tiny muscles. Madou and his group have developed "artificial muscles" that cover microscopic perforations in the 2.5-centimeter-long plastic capsule. The muscles—made of a porous, gel-like polymer—shrink and swell on command, controlling tiny trapdoors that swing shut to cover each perforation. "We got the idea from a kid's toy, those miniature sponges that expand when you drop them in water," says Madou. Apply a negative voltage and the muscles contract, opening the trapdoors and releasing the drug; apply a positive voltage and the muscles expand, shutting the doors and cutting off the flow.

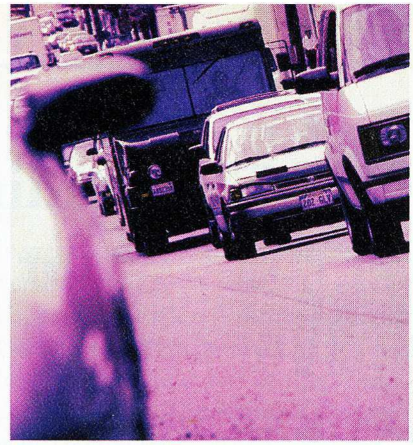
While Madou's artificial muscle attempts to solve just one part of the drug-delivery puzzle, his team's ultimate goal is to fabricate implantable capsules that come equipped not only with muscles, but also with tiny sensors, a battery and maybe even a microprocessor. The idea is that sensors would detect physiological changes in the body and relay a message to the battery, which would in turn produce the voltage to open or close the trapdoor. "Or instead of having sensors, the time of every dosage could be programmed into a chip, so that the right amount of drug is released at the right time," he says. Madou has co-founded a company, ChipRx, to commercialize the technology; company executives predict animal trials will begin in three to four years.

—Alexandra Stikeman



This microscopic image shows the gel-like polymer in its swollen state.

OHIO STATE UNIVERSITY



TONY STONE IMAGES

Beat the Jam

TRAFFIC | The trouble with traffic reports is they're real-time at best: By the time you hear about the mess, you may well be sitting in it. It's often too late for you to change your route, much less decide to take the train or stay at home.

But transportation researchers at MIT and the University of Texas at Austin think they can predict where congestion will strike 30 minutes in advance. Two traffic forecasting programs (DynaMIT and DYNASMART-X) are being tested in Irvine, Calif., and neighboring Anaheim, where highways and secondary roads are equipped with embedded magnetic sensors that detect passing vehicles and their speed. Historical and real-time data from the sensors fuel the prediction programs.

DynaMIT tries to predict the behavior of each vehicle. If traffic is light, the computer assumes cars will accelerate; if it's heavy, the computer predicts lane changes and heavy braking. The software simulates thousands of driver choices every few seconds, and predicts when these choices will converge to create a traffic jam, says Moshe Ben-Akiva, head of MIT's Intelligent Transportation Systems lab, which created DynaMIT. The University of Texas' DYNASMART-X is similar, but can make traffic predictions in smaller regions within a larger traffic system.

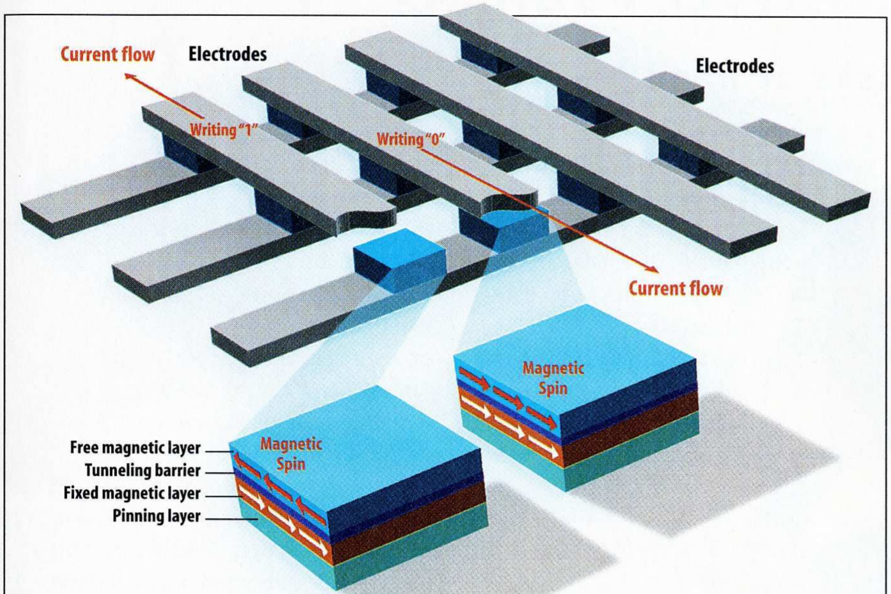
If testing goes well over the next two years, researchers may begin announcing the forecasts to the public. In anticipation of the system's catch-22—drivers who hear the forecast may render it moot by changing routes—researchers equipped the programs with a loop that predicts this effect and continually adjusts the forecast.

—Michael Vatalaro

eMail
Sent
Scott,
Remember that bet we made
when we both turned 30?
Looks like someone owes me $100.
-J
Done
Reply
Save
Palm Powered™ handhelds can do just about anything, anytime. Drop an email, fax
a lunch order, check inventory. That's taking the Internet with you. Simply amazing.
palm
Simply Palm
palm.com

UPSTREAM

SPOTLIGHT ON AN EMERGING TECHNOLOGY TO WATCH



In magnetic RAM, binary data ("0" and "1") is written by a current that orients the magnetic charge ("spin") in the free magnetic layer. The mobility of electrons through a tunneling barrier depends on the spins of the magnetic layers: If they are parallel, resistance is low; if they're anti-parallel, resistance is high. A pinning layer preserves the spin of the fixed magnetic layer.

BETSY HAYES; SOURCE: IBM RESEARCH

Computing's New Spin

Spintronics' initial payoff could be instant-on RAM

IMAGINE A COMPUTER AS powerful as the one sitting on your desktop—but small enough to fit into your shirt pocket. Or try a less ambitious concept: Turn on your PC and watch your software programs come up instantly. Gone is all that tedious booting up. As a bonus, you won't lose your work when the fuse blows.

Both of these concepts could grow out of the emerging field known as "spintronics." Experts say instant-on memory could hit the market in five years, and the miniaturization of computing enabled by spintronics will then gain momentum as the technology moves out of the R&D pipeline.

In today's computers, a divide separates the system's logic from its long-term memory. The central processing unit (CPU) and the short-term memory called RAM (random-access memory) operate by electronics. The hard disk, where the long-term memory resides, stores memory magnetically. Magnetic storage is great for packing in vast amounts of data and, unlike most existing semiconductor memory, it can store information permanently. But so far, magnetic-based memory has lacked the speed needed to keep up with real-time computing. That's why you need to reboot every time you start up your personal computer: Your PC is shifting the programs from the hard disk to the semiconductor-based RAM memory.

Now physicists and computer scientists are learning the magnetic tricks that could close this divide. At least 10 corporate labs, including those at IBM, Motorola, Hewlett-Packard and startup Integrated Magnetoelectronics, are working on prototypes of magnetic RAM (MRAM). The new memory chips promise an unmatched combination of instant-on capability, reduced power consumption, speed and density.

The technology needed to make all this come true is magnetoelectronics, or simply spintronics. It exploits magnetic properties in layers of materials only a few atoms thick, taking advantage of an electron's spin as well as its charge. "We are manipulating these structures on the atomic scale...something people didn't think was possible even 10 years ago," says Stuart Parkin, a physicist at IBM's Almaden Research Center in San Jose, Calif., and a pioneer in the field.

Already, Parkin's work on one early form of spintronics—"giant magnetoresistance," or GMR—has revolutionized the hard-drive industry by giving read-heads the ability to detect much tinier bits *(see "The Big, Bad Bit Stuffers of IBM,"* TR *July/August 1998)*. But today's most feverish research—by Parkin and others in corporate and government labs—is focused on MRAM, using a form of spintronics called "magnetic tunnel junctions." Devices that incorporate these junctions are similar to conventional RAM with a key exception: They rely on the quantum effect of electrons tunneling from one magnetic layer to another to write and read binary bits of information.

MIT physicist Jagadeesh Moodera—who built the first practical tunnel-junction device five years ago with his MIT colleague Robert Meservey—predicts MRAM could make hard drives obsolete. "Instead, you will have nonvolatile RAM, and that means you will have no more moving parts," he says.

Long-term, the linking of a tiny MRAM chip to a tiny magnetic CPU—with no need for a hard disk—could be a boon for miniaturization and pervasive computing. "Eventually a whole computer based on spin—that's the idea, that's the vision," says Stuart Wolf, program manager at the Defense Advanced Research Projects Agency, which has been a strong financial backer of spintronics. Such a computer, says Wolf, would be at least three orders of magnitude faster and use less power than conventional models. In addition, it "will be a hell of a lot smaller—to get the same computing power as you have in the box sitting on your desk, probably 1,000 times smaller."

That's going to take at least 20 years. Then what? Computers based on the spin of single electrons, Wolf says. "These spin devices will be the ultimate in nanoscale," he says. "You can't get any smaller than an elementary particle. At least, that's what I think now." **—David Talbot**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Minimize risk. Maximize opportunity.

Populist Power Tools

I WAS RIVETED BY THE LEGAL showdown over the song-swapping software Napster even before those Metallica millionaires started carping about losing their livelihood, and their disgruntled fans began smashing CDs in protest. Beyond the drama, rhetoric and legal verdicts, I've become convinced the Napster case represents a transformative historical moment.

The way I see it, some *38 million* Napster users toppled a central holdover fallacy from the Old Economy: that knowledge can comfortably be treated as a commodity. Let's face it. With populist power tools like Napster, digitized knowledge simply will not remain shrink-wrapped.

In this sense, the take-home message about Napster was evident long before the deal it struck last November with media giant Bertelsmann AG, in which it agreed to charge users a subscription fee and share the profits. Such settlements aside, and no matter how pending lawsuits come out, the really big story is that grassroots file sharing is here to stay. In an economy increasingly driven by knowledge-intensive, "content-providing" industries from software to Hollywood, the implications are even bigger than, well, Britney Spears. Little wonder that EMI executive Jay Samit has warned that the highly centralized music industry is merely "the canary down the digital mineshaft."

Known as peer-to-peer, or P2P, systems, grassroots networks like Napster, Gnutella and Freenet will keep expanding. Like so much of the New Economy's best, these systems feed off the decentralized power of the network itself. They allow users discretion to seek information from others as well as to pass around whatever information they possess. Even with these first-generation P2P tools, we can no more hope to keep a centralized rein on copyrighted material than the old Soviet regime could hope to control publishing by preventing access to copiers. Call them pirates, but Napster users perceive a bounty out there and view their system as an empowering way to share it—much like a turbocharged public library.

Ironically, especially in light of Napster's new subscription fee, the essentially noncommercial "sharing" quality of P2P systems is precisely what makes them so threatening to knowledge-intensive industries. It is also what makes the Napster phenomenon so fascinating: We stand deadlocked between two unworkable systems. The penchant of the P2P principals to freely share music includes no way to compensate the innovators who create content. Meanwhile, record labels are belatedly trying to add digital watermarks and other security features to recordings as they watch their intellectual property leach away. In a P2P world, these efforts are doomed as long as the industry insists on treating its wares like tangible packaged goods.

The take-home message from Napster: Songs won't remain shrink-wrapped. We'd better get used to it!

Perhaps most fascinating of all is how many smart people seem determined to willfully resist the central lesson of Napster. Their argument seems to be that exchanging songs via Napster is no different than stealing a stereo or guitar because both the songs and the physical items are the result of knowledge work. *(See "Your Work Is Mine!"* TR *November/December 2000.)*

All may spring from human labors, but maddening though it may be, new technologies like Napster force us to see just how different a Metallica song really is from any physical product. P2P systems like Napster powerfully exploit the fact that knowledge can be replicated without being depleted—unlike guitars, stereos, jackets and cars. In so doing, these systems use brute force to highlight the inescapable sense that the zero-sum calculus of the Old Economy is insupportable when the marginal cost of producing—or reproducing—something drops close to zero.

This emerging view extends far beyond Napster. We see it in software, as open-source programming gains ground despite a shaky economic foundation. We see it even in pharmaceuticals, as pressure mounts for firms to make drugs more widely available to Third World patients. To some extent, perhaps, our new capabilities to share knowledge compel us to find better ways to do so. In the end, this could explain Napster's broad appeal and stand as its most lasting legacy. It's not so much the old cry "information wants to be free," but rather a growing sense that it is impractical, unpalatable—maybe even unethical—to lock up the fruits of the knowledge economy when it costs virtually nothing to share them.

Only when we stop fighting this boundless-but-problematic aspect of the New Economy can we begin to constructively address it. P2P systems present us with truly revolutionary ways to share art, ideas and know-how. Moving out of the largely unedifying courtroom quagmire, the real question is: How can we best take advantage of these populist power tools while continuing to nurture an innovation-driven economy? ◊

Seth Shulman writes widely about science, technology and intellectual property. His most recent book is Owning the Future *(Houghton Mifflin, 1999).*

PHOTOGRAPH BY FURNALD/GRAY

ination.

7) higher Internet stock trading volume than any other investment bank.

8) a tech commitment demonstrated by the firm's own equity investments.

9) TechTalk, the groundbreaking Webcast that delivers insight straight from the source's mouth.

10) the TechBrains Advisory Board of visionaries such as George Gilder and Clay Christensen.

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Be bullish.

Lou Gerstner of IBM

What New Economy?

"I resist the idea that there is a new economy—something that is separate and distinct from some other economy."

Q & A

When former American Express and RJR Nabisco executive Louis Gerstner Jr. arrived at IBM in April 1993, he took the helm of what seemed like a sinking ship. The company was hemorrhaging money, had lost its direction and, it seemed, its will to compete. Plans were in place to break IBM into smaller, independent businesses. But Gerstner shelved those plans and told his charges their hopes lay in wielding the sweeping power of the existing Big Blue, if it could be retooled for a new day of unceasing competition.

The turnaround has since become legend. Gerstner pushed IBM into the services business, now the fastest-growing segment of the roughly $90 billion company. Big Blue has also branded itself as the e-business leader, while continuing to innovate in storage, semiconductors, database technology and high-end computer systems.

PHOTOGRAPHS BY JAMES LEYNSE/SABA

However, as Gerstner—Lou to employees—stresses, there is never room for complacency. Last July, the IBM chairman and chief executive officer reorganized the firm to focus more sharply on the twin needs to protect and build current businesses while also going more aggressively after emerging opportunities—in particular by applying its computing and database expertise to plumb huge opportunities in genomics and the life sciences. In one of his most detailed interviews in recent years, Gerstner exchanged multiple e-mails with *TR* Editor at Large Robert Buderi about his brand of leadership, where IBM is headed, e-business and the promise of information technology.

TR: You came to IBM when the company was losing billions annually and had suffered a seemingly mortal blow in its ability to innovate. What were the major challenges back then?
GERSTNER: Even back in the dark days of 1993, I never believed that IBM's technical community had lost the spark of innovation. If anything, one of the frustrations our technologists felt most acutely—along with our customers and shareholders—was that the company was too consistently slow to seize innovation, turn it into products and get them to market. That was a much bigger institutional shortcoming than a lack of innovation.

So that gap between our labs and the marketplace was one problem. It made us slow in an industry where being first is almost as important as being right. We were also in a prolonged three-geography [spanning three continents] recession, which naturally affected us more than it did a lot of our less-global competitors. The image of the mainframe was in a ditch. Our cost structure had been allowed to get way out of line with our competition, and the IBM workforce was dealing with the first wide-scale layoffs in the company's history.

We took advantage of the crisis to move fast and get our financial restructuring behind us. We had to do that, because we also had to break the organization's very natural, but very debilitating, obsession with "the problem." We had to shift the mindset away from internal issues and institutional self-analysis to external issues, getting back into the marketplace and stringing some wins together.

TR: What are the major challenges today?
GERSTNER: I'd group them into two broad categories. Obviously everything starts with e-business, which will drive most of the customer investment in this industry for years to come. Our strategy is in place and makes sense to our customers, partners and investors. We have a strong set of products and services to offer against that strategy. So today, our leadership team spends most of its time on the gritty issues of operations, execution, implementation—sales execution, distribution channels, driving sales to Internet fulfillment, building speed to market. And building a culture that always, always focuses on the marketplace—customers and competitors.

So operational leadership is one priority. The other is technical leadership. With every industry being swept along by the e-business revolution, there has never been a higher premium on the ability to innovate. I don't know how any company competes today without a thriving research and technical capability. There are major strategic battles being waged right now: in UNIX servers; in the software layer known as "middleware"; in a big shift in the semiconductor business, where the center of gravity is moving away from PC processors to high-end server-class microprocessors at one end, custom logic chips at the other and network processors in between. Last fall we announced a $5 billion investment in our semiconductor business to go after this opportunity. We're playing a multidimensional game here—battling today's competitors for immediate marketplace success, and investing in potentially game-changing, longer-term opportunities.

"I don't know how any company competes today without a thriving research and technical capability."

TR: What will high-end server-class microprocessors, network processors and custom logic chips do for us?
GERSTNER: What's happening in the semiconductor marketplace is not so much about what the chips are going to do for us, as what we are choosing to do with our computers. We have entered a post-PC era. The self-standing, self-contained personal computer is no longer going to be the locus of interest and investment in this industry. In just a few years, non-PC devices like personal digital assistants, data-enabled cell phones and game consoles are going to make up well more than half of all Net access devices. There will be hundreds of millions of PCs in the world, but billions of other Net access devices. Coming right behind that, perhaps trillions of "things" we'd never call computers: household appliances, machine tools, medical devices, our cars. All of them will be outfitted with the ability to communicate, and with specialized, energy-efficient, inexpensive chips—which are a very different animal altogether than the brains inside today's personal computers.

So that's one end of the spectrum. At the other, chips for the big servers. Workloads are shifting off desktops to the infrastructure of computing and communications. The demand for transaction processors and Web servers is going to explode in the years ahead, because these are the systems that make sure e-business applications can scale, are available, reliable and much more secure than applications have had to be in the past.

And finally, if we're going to realize the full power and potential of doing real e-business, the networked infrastructure is going to have to advance in leaps, not increments. The Internet we know today will look primitive in five years. Before long, we'll see traffic moving over the Internet increase 1,000-fold, so we're going to see explosive demand for chips to power chips in the networking and communications gear that keeps all of the digital information moving at high speed and bandwidth.

TR: How do last summer's management changes address these challenges?
GERSTNER: You're never going to implement a strategy without a structure that reinforces and complements it. We've evolved our e-business strategy for four years now. And we're to the point in that strategy that it has taken hold in a way that an entire new market is exploding all around us. So the thing we need most right now is a very, very focused execution capability in the company.

At the same time, it's pretty clear that we're already moving out of the first phase of e-business. In the first phase, the killer app was business-to-consumer e-commerce—the race to offer all kinds of retail services

> "There is a market emerging now around the marriage of information technology with life sciences research and genetics that…represents the next major revolution."

on the Net, from stock brokerage to cars, loans, flowers and pet food.

In this next phase, we're going to see a few things happen. Enterprises are going to get beyond e-commerce and integrate the entire enterprise using networked technologies. This includes business processes and relationships with other enterprises and industries, which is fueling all the interest in B2B [business to business] solutions. We're also going to see a proliferation of applications deployed to take advantage of all kinds of Net access devices. We've been spending billions of dollars getting ready for this new world, to build out—with our customers, with telcos [telecommunications companies], with service providers—the enormously sophisticated infrastructure that will be required to support the next generation of e-business.

So the organizational moves we made last summer delineated these two related, but very different, business imperatives: executing today's e-business strategy and seizing emerging opportunities in the next phase of e-business and beyond.

TR: What differences have you found in running a technology-based company versus an American Express or RJR Nabisco?

GERSTNER: One, they're all competitive, but I've never seen an industry that's as intensely, consistently and relentlessly competitive as this one. In every other industry I worked in, you could list the competitors and go back 10 or even 20 years and they were all the same. Today, every time you open the newspaper, there's a new competitor—a real one—staking its place in this industry. I've heard people say this is a business for young people. I understand the thought behind that, but I disagree. This is an industry for hungry people. It's "eat or be eaten." And your appetite has to be big, or you're going to look around and find out that someone else has carved up and devoured your customer base and market share.

The second thing I'd mention is speed. No industry on earth moves as fast as this one. Ever since the days of the first PC in the early '80s, technical advance has come on shorter and shorter product cycles. Today, even in an industry known for speed, the rate of change is unprecedented, and it's only being accelerated by the Net. It's fun. It's a challenge. But if you pause, say good-bye.

Finally—and I don't want to gloss over this—this is an industry that does create things that make the world a better place. Every government in the world recognizes that investments in information technology are essential to their ability to drive economic development and the prosperity of their citizens. This is an industry that matters in ways far more profound than speeds and feeds and terabytes and areal densities.

TR: Going back to e-commerce: You stunned analysts a while back when you said most companies—including e-commerce companies—didn't really understand e-commerce. Can you explain that?

GERSTNER: First, a couple of years ago, right in the middle of the so-called New Economy, and the near-hysteria over all the Internet startups coming to destroy the entrenched brand names in every industry, I raised a few eyebrows when I called the dot-coms "fireflies before the storm." I said the real storm was going to hit when all those established businesses moved to exploit network technologies to reinvent their brands, customer relationships, supply chains and distribution systems. Well, that storm has arrived.

A year later, however, it seemed like we were lurching from dot-com hysteria to what I described as "dot-com alchemy." It was unlike anything I've ever seen—a frantic attempt by some established businesses to pull off some kind of quick strike—to do something, anything, with the Internet just to show they were participating in the digital economy. What I was suggesting is that while the Net is a powerful vehicle for business transformation, it does not give anyone a free pass on basic business management—setting a solid strategy and implementing it well.

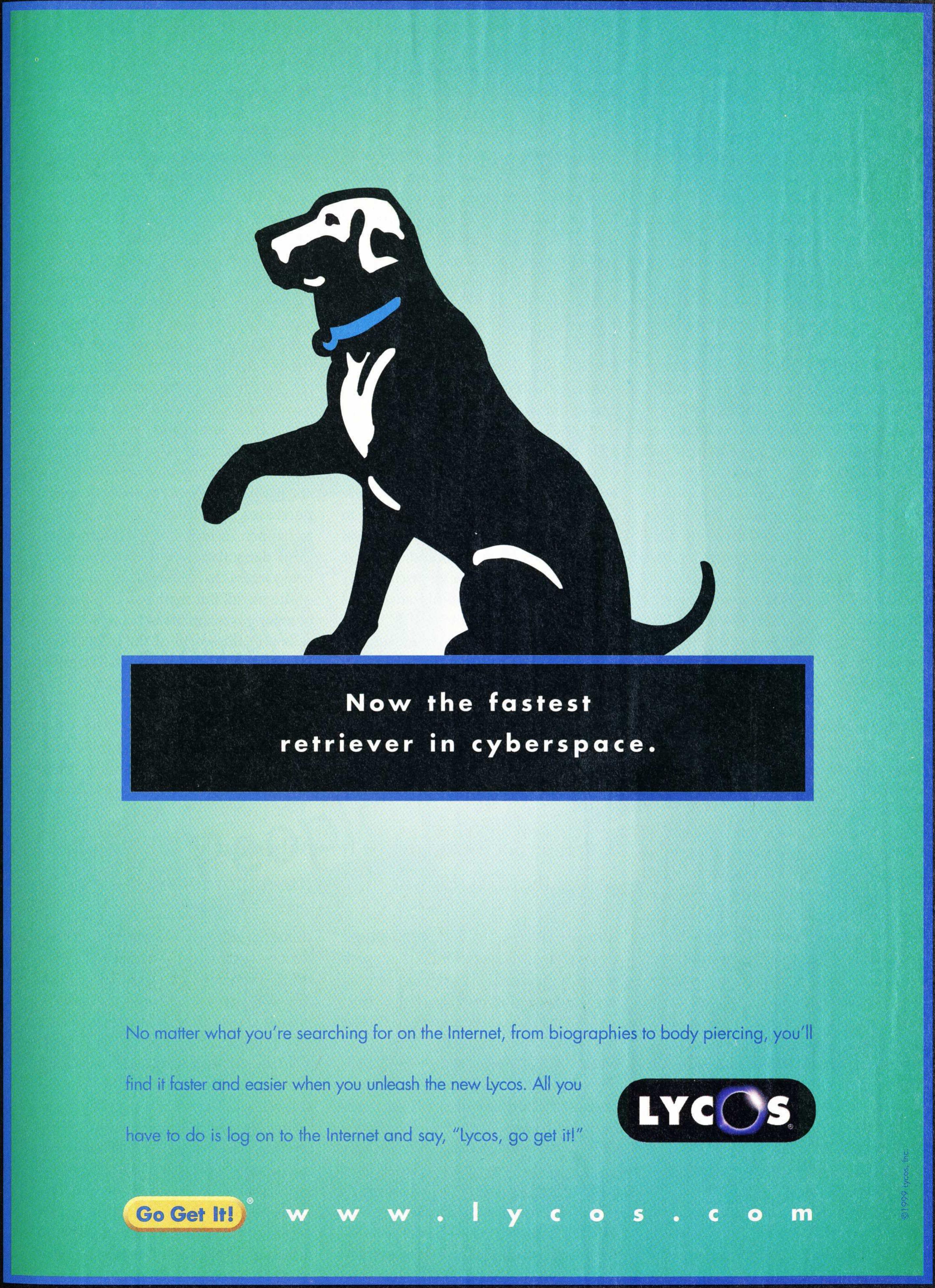
TR: So how would you characterize the New Economy?

GERSTNER: I resist the idea that there is a new economy—something that is separate and distinct from some other economy. Is the Internet, and is investment in information technology, driving a sustained period of economic expansion? Yes. But we have to be sure we understand the Internet is not killing off other technologies or industries, and it is not obsoleting all that came before it. The Internet is going to be remembered a lot like the way we see the impact of the electric motor today—first used in heavy industry, but eventually absorbed and adopted by every industry.

There's been far too much emphasis on catchy ideas like this so-called New Economy, or new kinds of competitors, or new business life-forms. The enduring impact of this transformation isn't going to be found in the meteoric rise of some new invention or business construct. It's going to be about all the existing enterprises in the world figuring out how to win the battles inside their industries against their traditional competitors. That's true whether we're talking about pharmaceutical companies, manufacturers, financial services firms, universities competing for students or the best faculty, or governments competing for new investment.

TR: Related to this, can you say more on where you see IBM going in the next few years? What about 10 years down the road?

GERSTNER: Services is our fastest-growing business. We lead the industry on virtually any dimension you could pick. It's a unique business, unlike any I've ever seen in terms of its ability to continually reinvent itself and generate new opportunities. We're certainly seeing that now, with a whole new category of services developed expressly for e-business. That's everything from huge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All that said, we're not leaving behind our core businesses in computing infrastructure—servers, storage, networking and middleware—to morph into a services business. Look at the marketplace. E-business is driving an explosion in transactions, data flows and workloads. That drives huge requirements for a new generation of computing infrastructure to support e-business: more flexible, scalable, reliable, intelligent and self-managing. Building infrastructure—that's our franchise.

The final point I'd make is that our customers don't come to us as a product shop, or a "body" shop, or as a software business, or as a strategic consultancy, or as a research and development organization, though we're all those things. Our customers bring us their most sophisticated business challenges, and they expect us to tailor information technology solutions drawn from a portfolio that spans high-end consulting to maintenance. They look to us to integrate the technologies with each other, and with their business strategies. This requires that we strengthen our leadership in both services and technology. That's what we do.

TR: Any thoughts on "the next big thing"?
GERSTNER: Well, first of all, we've got a long way to go on e-business. We're about five years into a transformation I expect to take another 20 years.

However, there is a market emerging now around the marriage of information technology with life sciences research and genetics that I personally believe represents the next major revolution—not only in this industry, but for society at large. We're going to do things like simulate the birth of cells, understand things we can't even begin to examine today and potentially find ways to build new drugs to combat heart disease, genetic defects, cancers.

A year ago, we launched a $100 million supercomputing project called Blue Gene to explore one of the great mysteries of genetic science: the way proteins fold to form healthy or diseased cells. To do it will require computing on a scale that has never been attempted before—petaflop speeds, one quadrillion operations per second. But we've been getting ready for this one for a long time.

Even today, I don't think most people know it, but the chess match between the Deep Blue supercomputer and Garry Kasparov was really a big, public laboratory where we were refining a new approach to computing. We were learning how to marry very sophisticated algorithms with massively powerful processing to attack profoundly difficult problems. What we learned in that chess match and all our subsequent "deep computing" work is being applied now in partnerships with major medical centers, universities and pharmaceutical and life sciences companies to lead this revolution in biology and health.

TR: How do you value the role of science and technology inside a company as sales- and marketing-driven as IBM?
GERSTNER: When I arrived at IBM in 1993, the first IBM site I went to was the [Thomas J.] Watson Research Center in Yorktown Heights, N.Y. I went there because I wanted those researchers to hear from my own lips that if IBM was going to survive and rebuild, we were going to do it around our very rich history of innovation and technical leadership. I wasn't pandering. I came to IBM with a firmly held conviction that at our core, we were—and are—a technology company. If that's not working, we can't compete.

Seven years later, it's working just fine. I mean, going into our R&D labs around the world remains one my favorite things to do. The record of achievement is mind-blowing: Deep Blue. Prototypes of quantum computers. Holographic storage. Chips that will power the next generation of Net access devices. The most powerful supercomputer technology on the planet and all the software and servers that power the most heavily trafficked sites in the history of the World Wide Web. Believe me, every CEO I talk with eventually gets around to asking how his or her organization can get access to this foundry of innovation, and to our technologists themselves.

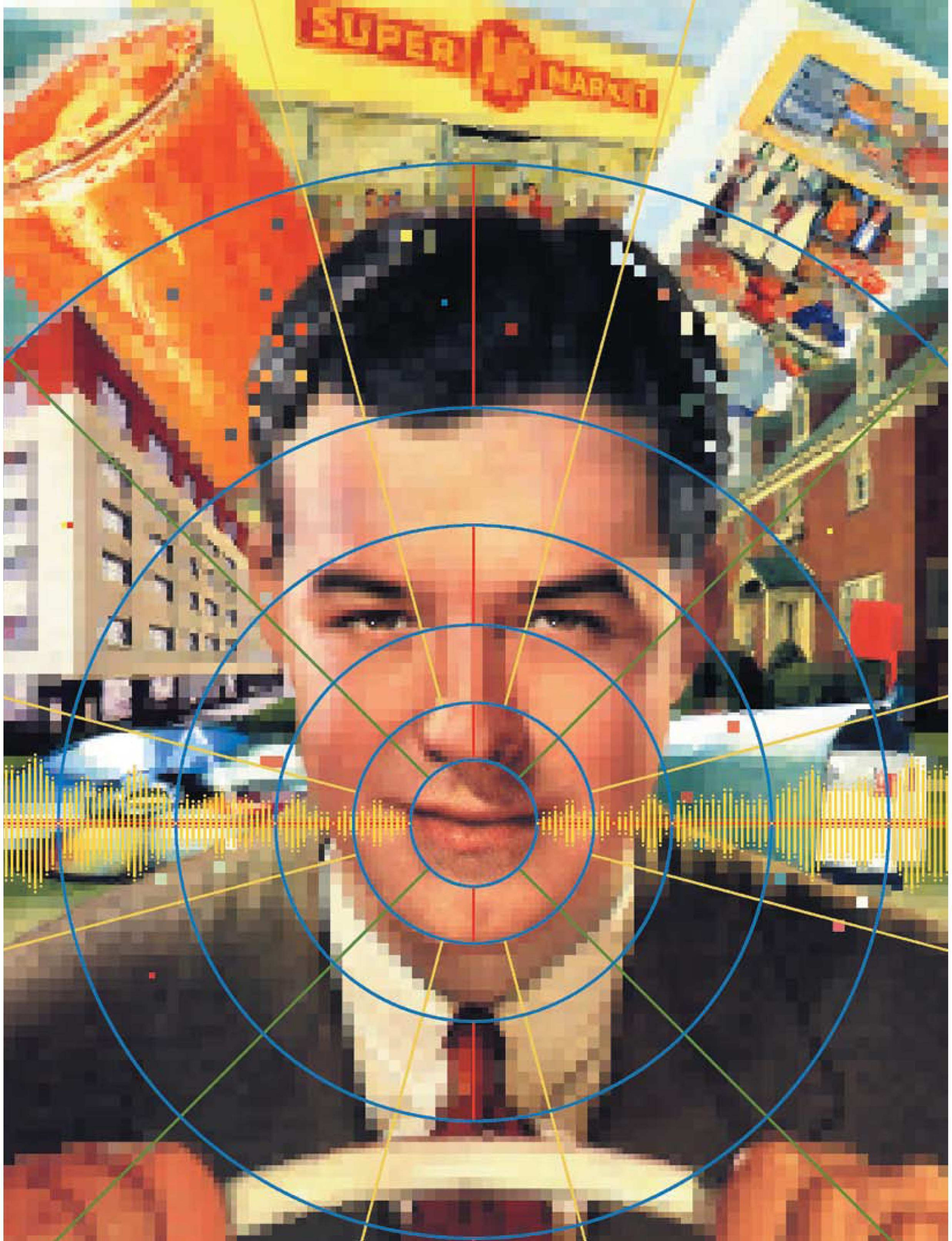
So, I'd tell you that I entered IBM with a deep respect for the company's technical heritage, and that has only grown over the last seven years—seven years, by the way, in which IBM technologists have earned more U.S. patents than any other company in the world.

TR: To end on a personal note: What excites you most about technologies in your labs?
GERSTNER: You said "personal." All right then, let me talk about an issue that is both my greatest concern about this networked world, and at the same time my greatest source of hope about what's possible here. There are a lot of people who believe a networked world is going to fortify the so-called digital divide—they see it creating a bigger gap between the people in the world with access to information and those without. That's a legitimate concern. But it is not the predestined outcome.

We've already talked about this explosion in low-cost access devices. One implication is obvious. We're going to have the chance to take unprecedented levels of service and information to the entire world, without requiring people to purchase a full-blown PC. Now, a lot has to happen in terms of telecommunications deregulation and competition to bring access charges down in many parts of the world. But there's an opportunity here for governments to bring their citizens into the world of the information "haves" and to join this revolution, rather than standing outside looking in.

I was with 300 European business leaders at a conference on e-business last fall. I talked about e-procurement, e-commerce, e-service. Then Shimon Peres spoke, and said I had forgotten to talk about one of the "e's"—e-peace. He then went on to talk about a school in Palestine where they have put computers in an Arab and Israeli neighborhood. The technology allows children to reach out to one another. His point was that these children will have a new chance to grow up without the biases of their parents and of the older generation. So, this technology isn't just about competitive advantage and market share and productivity in a commercial sense. This technology touches all of society—schools and governments, universities, health care—every part of the lives we live, and it really can make the world a better place. ◊

> "The Internet is going to be remembered a lot like the way we see the impact of the electric motor today."


SUPER

Not far from the modest office where, 30-odd years ago, Douglas Engelbart invented the mouse, multiple-window screens and other mainstays of personal computing, an SRI International computer scientist approaches a mock-up of a white convertible—representing the car of the future. He plugs a notepad-sized computer into the dash, and at once the vehicle's 1,400-odd computerized systems become accessible through a simple user interface. Using voice commands, he demonstrates how he can request a CD track, link wirelessly to his office to check voice mail or have his e-mail read aloud by a speech synthesizer. One message is from his refrigerator asking whether he'd

Computing GOES Everywhere

THE DREAM OF "UBIQUITOUS COMPUTING" HAS BEEN AROUND FOR A WHILE. NOW IT'S SERIOUS ENOUGH THAT A COMPANY LIKE IBM IS WILLING TO THROW $500 MILLION AT IT.

BY ROBERT BUDERI

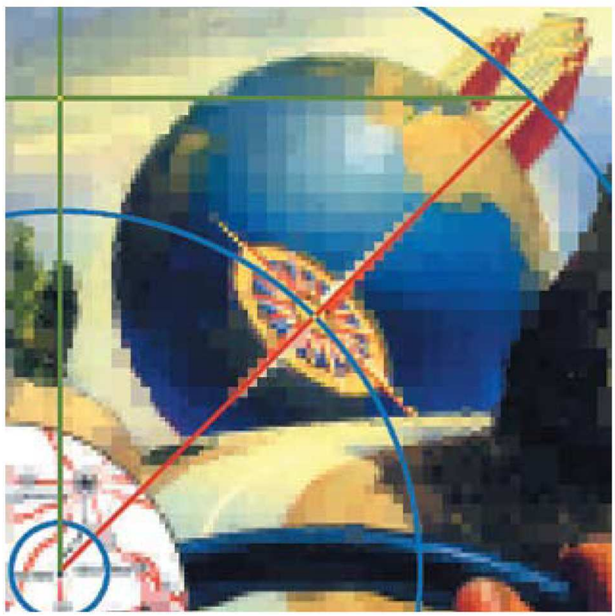
like to pick up orange juice on his way home. "Show me the grocery stores," he orders the car. The vehicle quickly accesses the Internet and relays directions to the nearest supermarkets.

Shopping done, our motorist arrives at his apartment, where the Collaborative Home e-Fridge (CHeF) is waiting for the OJ it requested. The juice is duly logged in, but when lemonade is removed, the fridge announces it's now out of lemonade—and asks whether the item should be added to the shopping list. CHeF even knows the pantry contents. So when asked to suggest something for dinner, it flashes the recipe for a chicken dish on its screen: in-stock ingredients are highlighted in green, those missing appear in red, while absent items already on the shopping list are rendered in blue.

ILLUSTRATIONS BY JOHN CRAIG

Ah, the future of computing. Whether it's with refrigerators, in cars, around the office or on the high seas, powerful new systems that you can access through words and maybe even gestures—and which will then scurry to invisibly do your bidding—are promising to friendly-up the world. The dream is called "ubiquitous" or "pervasive" computing—and it's fast becoming the hottest thing in computer science. The ultimate aim is to seamlessly blend the analog human world with all things digital. That way, either by carrying computing and communications power with you, or by accessing it through an infrastructure as widespread as electric power is today, you will tap into this world on your terms and in your language, not a machine's.

Less than a decade ago, such dreams were confined to far-out future factories such as SRI, Xerox Corporation's Palo Alto Research Center (PARC) and MIT's Media Lab. But recent advances in computing power, storage, speech recognition and especially wired and wireless networking, coupled with the rise of the World Wide Web, are bringing the dream within grasp of the real world. That essential truth explains why Microsoft and Intel, which built their fortunes on the stand-alone personal computer, are shifting gears toward this new, mobile, networked world. IBM has just committed nearly $500 million over the next five years to study pervasive computing and create the hardware and software infrastructure to support it. Other players include Sony, Sun Microsystems, AT&T, Hewlett-Packard (HP) and just about every corporate or university computer lab worldwide.



Uncertainties abound. Fights are under way over competing technologies and standards; and no one even knows how many computing devices people will want to carry in the future, let alone what type. Still, the field is maturing rapidly. Researchers agree more uniformly than ever on where technology is headed—or at least on which main paths it's likely to take. This allows what was previously a hodgepodge of visions and predictions about the future to now be classified into three broad technological frameworks: 24/7/360; who, what, when, where; and the digital companion.

While these categories—signifying the importance of pervasiveness, awareness and personalization—don't capture every aspect of ubiquitous computing, they do describe its essence. And just by walking into computer labs these days, you get the strong sense that the progress made in addressing these challenges has computer scientists convinced a major breakthrough is within their grasp. "Ubiquitous computing is viable—and will soon be commercially practical," asserts William Mark, SRI's vice president of Information and Computing Sciences. "The revolution is about to happen."

24/7/360

The widely acknowledged father of ubiquitous computing was the late PARC computer scientist Mark Weiser, who coined the term in 1988. Weiser described a world where each person would share thousands of highly distributed but interconnected computers. This computing power, he argued, should blend into the background, hidden from people's senses and attention.

In the early '90s, PARC researchers created ParcTab, a handheld display that connected via infrared signals to a network computer so researchers could access files without being tied to their desktops. Other trailblazing work took place at the Olivetti Research Laboratory in Cambridge, England (now AT&T Laboratories Cambridge), which pioneered the Active Badge. The badge transmitted an infrared signal that allowed people to be tracked throughout a building via wall-mounted sensors—among other things, enabling phone calls to be forwarded automatically to their location. And then there was the ultimate popularizer—MIT's Media Lab. Researchers at this largely industry-funded lab spread the word about concepts such as news-gathering software agents that would tailor each morning's electronic newspaper to an individual's tastes.

These early steps have now loosed a flood of innovation and promise at computer labs worldwide. Today, it is a fundamental tenet of ubiquitous computing that computational power and services will be available whenever they're needed—that's the 24/7 part. And not just throughout a building, but everywhere—that's the 360, as in degrees around the globe. Under the 24/7/360 umbrella, however, lie two radically different approaches. One continues the drive to push computational power into objects with ever smaller footprints—via souped-up laptops, handhelds and wearables. The other holds that tomorrow's computing resources will not be carried on specific devices. Instead, they will live on networks. In this view, much as people tap electric power by plugging into any outlet, so should applications and files be reachable from any display or information appliance—be it in a car, hotel or office. The network, to paraphrase the folks at Sun, *becomes* the computer.

This utility-like model of computing is catching fire at companies that build the backbone for the Internet and for enterprise computing networks—the communications, applications, storage and services associated with corporate computer systems. Indeed, of IBM's recent $500 million commitment to pervasive computing, $300 million will go toward building an "intelligent infrastructure" of chips, mainframes, servers, databases and protocols for supporting the data-rich, mobile future.

Sun's take on this idea is evidenced in its four-year-old Public Utility Computing (PUC) project. The aim is to create dynamic virtual networks, or supernets. Each supernet would

be assigned a public Web address that its members contact. After authenticating themselves through a password or smart card, users would receive the encryption keys and addresses for entering the private supernet—where they could securely retrieve files and collaborate in real time. With PUC, there is "no distinguishable difference between being in HP's conference room or in my office, or at home, or at the beach, or in New York," asserts senior manager Glenn Scott.

PUC technology could also allow organizations to store and retrieve data and access sophisticated computational services, such as database software that analyzes customer trends. Only instead of purchasing these expensive systems, companies would pay solely for what they used. This might be ideal for small businesses, argues Scott. Imagine a 10-person operation that wants to tap big accounting software requiring a high-powered machine that the outfit can't afford. Under the PUC concept, he says, the firm could simply "rent" the application as needed, perhaps once a week for 10 minutes. Since PUC works at the network level rather than inside the software, any application can be easily brought into the supernet. This, says Scott, makes it far more powerful than the pay-as-you-go systems offered by today's applications service providers.

The catch comes in making everything secure. Scott says field trials last year validated the concept for communications and storage, which are mainly concerned with encryption of the data—both when it is being transmitted and once it is stored. But providing secure computation—assuring users their data isn't inadvertently copied, for instance—is more dicey. Any solution will likely involve securing both hardware and software—a tricky combination Sun is only just exploring. Still, Scott believes PUC is the way of the future; and Sun has filed 13 patents around the technology.

This utility concept looks years ahead—but others are taking more immediate aim at a scaled-back form of 24/7/360. Since 1998, what is now AT&T Laboratories Cambridge has made its Virtual Network Computing software available free for download. VNC turns any Web browser into a remote display for a desktop computer, allowing people to access files and applications from just about any device—laptop to PC, Mac to Palm. What's more, it works on standard telephone lines and cell phones—lightening the data stream by transmitting only the bits or pixels that change from second to second.

It's the same principle as PUC—on a more personal level. The reason people carry bulky laptops is not to have all their data at hand, argues AT&T researcher Quentin Stafford-Fraser. "What you really want to carry around with you when you're going somewhere is your environment," he says. That means your sets of preferences, dates, desktop and so on. With VNC, he notes, "I can pretty much go anywhere in the world and be connected through to my machine that is sitting on the desk here."

The system isn't secure, and it doesn't offer the file-sharing capabilities of PUC. Still, its cross-platform capability is compelling—as AT&T researchers found when one corporate user's network server crashed while its systems administrator was off camping. Reached on his cell phone, the technician was told to return 250 kilometers to the office. Instead, he whipped out his Palm Pilot, called up his VNC-enabled desktop and fixed the problem—all without leaving his tent.

Stafford-Fraser reports there are as many as 10,000 VNC downloads a day—with about a million machines running the software. But that's a blip on the screen compared with what AT&T and others believe might be the prime player in 24/7/360 for years to come: the already ubiquitous telephone. This idea is embodied in AT&T's VoiceTone project, which seeks to replace a normal dial tone with an automated version of yesteryear's know-everything switchboard. "AT&T, how may I help you?" the voice tone might inquire. Thanks to speech recognition, speedy processing, the Web presence of just about everything, and technologies such as text-to-speech synthesis, callers can ask for messages and traffic reports, check the weather and sports scores, or make restaurant reservations—all in normal language and without logging on in the conventional way.

BEYOND THE TECHNOLOGICAL CHALLENGES OF BUILDING AN INFRASTRUCTURE FOR UBIQUITOUS COMPUTING LOOM MIND-STAGGERING ISSUES THAT RUN FROM PROGRAMMING FOR THE NETWORKED WORLD TO THE FEAR OF BIG BROTHER-LIKE INVASIONS OF PRIVACY.

AT&T is developing some of these services itself. However, many will be provided through voice services concerns such as Tellme Networks of Mountain View, Calif., in which AT&T has invested $60 million. Tellme and competitors such as Santa Clara-based BeVocal seek to turn ordinary telephones into gateways to the Web. At Tellme, for example, callers dial an 800 number, then navigate the system with spoken commands such as "Restaurants," "Boston, Massachusetts," "Chinese." They then get a list of candidates—and can even hear Zagat reviews. If they wish to make a reservation, they're connected to the restaurant free of charge.

Tellme co-founders Angus Davis and Mike McCue left Netscape to pursue the vision of telephone-as-computer-interface. "We were these browser guys, and we thought it was cool that there were 150 million Web browsers," explains Davis, Tellme's director of production. "But we thought, wouldn't it be really cool if we could build a user interface to the Internet that reached two billion people? And that's what made the phone exciting."

Who, What, When, Where?

Computing by the billions may be too much to hope for in the near future. Still, it's already clear that more and more computing power and services will reside in networks, and that these services will be increasingly accessible—through wires and wireless networks, and via myriad devices. Emerging software technologies such as Sun's Jini and Microsoft's Universal Plug and Play promise to allow systems and services to be accessed no matter what operating system or programming language they employ. On the hardware front, Dallas market research firm Parks Associates estimates that 18.1 million information appliances—things like handheld computers and Internet-connected TVs, mobile phones, car navigation systems and game consoles—shipped last year. Nascent wireless standards, such as Bluetooth for short-range radio communications, will add more

flexibility for linking between devices and networks.

But before even a few folks have the benefit of truly ubiquitous computing, great strides must be made toward creating technology that serves people rather than the other way around. That means objects and services must sense and respond to what is going on around them, so that they can automatically do the right thing—hold a routine call if you're busy, let you know if your flight's delayed, or inform you of a traffic jam and suggest a better route. Such feats are increasingly known as context-aware computing. However, to do this job to the utmost, networks must know something about the people using them, often including their identity and location. This will force a choice: do people want to periodically cede privacy in exchange for better service?

A lot of the effort to track people and devices—and coordinate their interaction—dates back to Olivetti's (now AT&T's) Active Badge program. The latest twist is called "sentient computing," which replaces the infrared-emitting active badges with ultrasound transmitters, dubbed "bats." Since ultrasound provides far more precise positioning data than does infrared, bats make it possible to construct a computer model that follows people, objects and their relation to each other. The computer, explains researcher Pete Steggles, creates a "circle around me that's about a foot in radius—and there's another little circle around this device. And when the one is contained in the other, then I'm in a sense the owner of that device, and appropriate things happen" (*see "Sentient Computing," below*).

In one application, the system is integrated with Virtual Network Computing. By pressing a button on their bat, users can have their desktop teleported to the nearest workstation screen. A more multifaceted use of the technology lies in the lab's context-aware filing system, which automatically stores the data people create—whether they're working on a computer, snapping a digital picture, dictating a memo or just talking to colleagues—in a personal time line, from which it's easy to integrate information with traditional files and applications.

For instance, Steggles relates, "The other day I took a bunch of photos for a presentation—and the shots were just there in my time line, so I could just drag and drop them into my PowerPoint presentation." What would have taken hours to transfer to his desktop, he adds, took mere minutes. Similarly, say you couldn't recall a reference a colleague gave when you were talking a few days earlier, and the person wasn't around to ask. Because the system also captures the context of what people do—including who else is in the room with them—the time line makes it far easier to retrieve such information as well.

Another way to track objects is through radio-frequency identification tags, like those used to monitor livestock. These "e-tags" range in size from a grain of rice to a quarter and so can conceivably be embedded in everyday objects. Most rely on inductive coupling, like that used in the bulkier tags placed on clothes to deter shoplifting. Unlike bats, e-tags have no internal power source that needs periodic replacement. Instead, a signal from a tag reader induces a current in the implant, which consists of a coil attached to a silicon chip. Energy captured by the coil is stored in a capacitor that powers the chip and causes it to transmit a unique identifier to the reader. From there, the data is relayed wirelessly to the Internet or company intranet—summoning more information relating to the tagged item.

Last year, PARC researchers e-tagged everything from paper to books to copier machines around the lab. That way, anyone

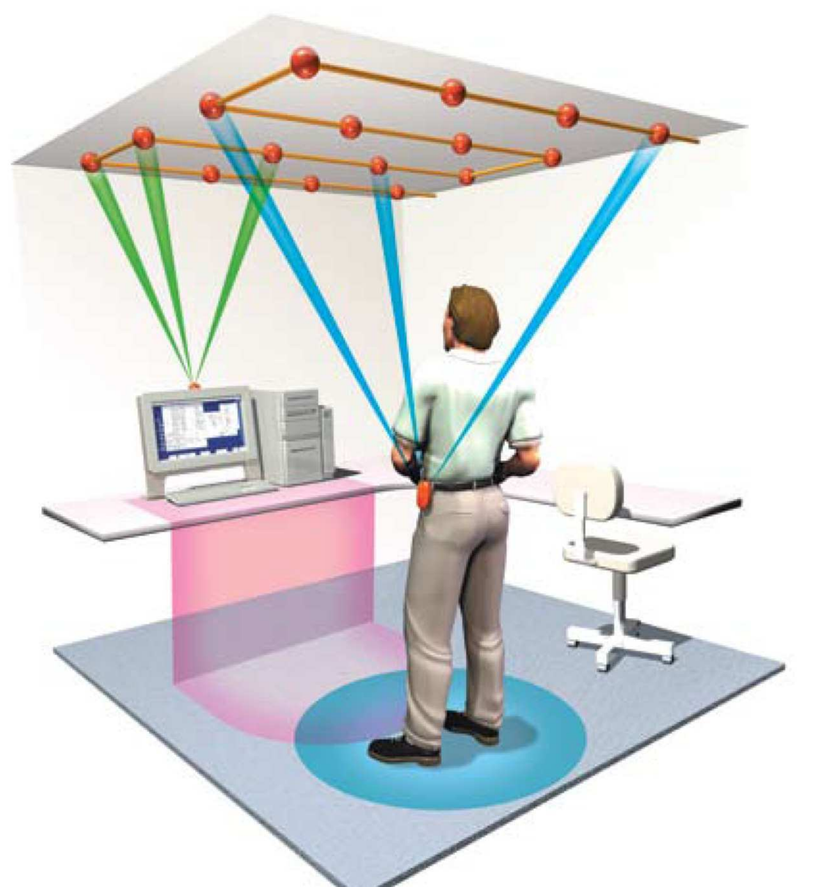
Sentient Computing

What if, by simply picking up an object, it became "yours"? AT&T's "bat" transmitters use ultrasonic signals to blur the lines between the human and digital spheres.

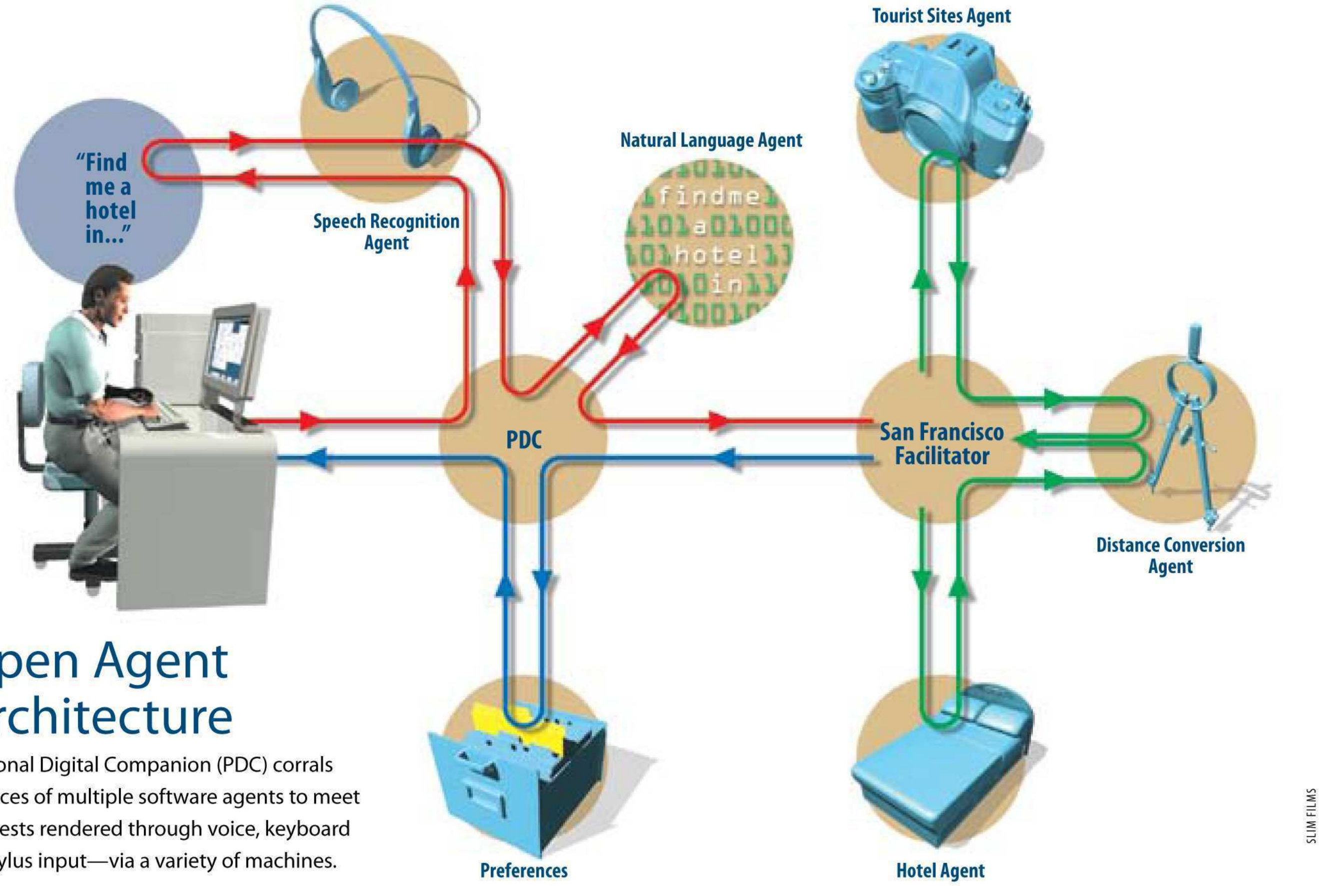
"Bats" are battery-powered, key-chain-sized ultrasonic transmitters that can be worn on a belt or placed inside objects. They broadcast an identifying 48-bit pulse to receivers embedded every 1.5 meters in ceilings: About 800 are placed around AT&T's three-story lab in Cambridge, England.

Since the speed of sound in air is known, comparing the signal's arrival time at three or more locations allows the bearer's precise position to be calculated.

Using this location information, a computer creates zones of "usage" and "availability" around objects and people. If a person's zone overlaps an object's zone, the person becomes the temporary "owner" of the device, be it a workstation, digital camera, tape recorder or anything else. There's no logging on. And everything users create—document, picture, memo—is automatically stored on a server in their personal files.



SLIM FILMS



Open Agent Architecture

Personal Digital Companion (PDC) corrals services of multiple software agents to meet requests rendered through voice, keyboard or stylus input—via a variety of machines.

REQUEST: User speaks into microphone, requesting hotel with pool in San Francisco, within 500 meters of Fisherman's Wharf, for two nights, starting May 1—and for under $200 per night.
UNDERSTANDING: PDC recruits speech recognition agent to listen to query. Recognized words are passed to a natural-language agent, which translates into a logical representation of English that other agents understand. Request returns to PDC as goal to be met.
AGENTS-AT-WORK: PDC breaks goal into discrete elements that are sent to specialized agents, including a San Francisco facilitator. One query goes to tourist sites agent, which locates Fisherman's Wharf. Hotel agent checks for affordable hotels with pools. Candidates are sent to distance conversion agent, which determines which are close enough to Fisherman's Wharf.
SOLUTION: Answer is returned to PDC, which checks user's preferences—for instance, Hilton vs. Marriott—and ranks choices. List can be telephoned, e-mailed or displayed on screen map, depending on where person is and what device is being used. Person makes choice and asks digital companion to book room.

carrying a tablet computer equipped with a reader could access additional information and services associated with the tagged item. Say, for example, a person approached a flyer announcing a lecture. By positioning the computer near the title, he or she could call up the talk abstract. Holding it near the date and time announcement, where a separate tag was embedded, would schedule the event in an electronic calendar. Even better, many tagged items activated services associated with their physical form. In one demonstration, bringing a tagged French dictionary near a computer summoned a French version of the English document then on the screen. Roy Want, who led the project but has since left Xerox for Intel, describes e-tags as "an evolution of the bar code. I think in the future almost anything that is manufactured and traded will contain an electronic tag." Such tags, he adds, will link to the Internet to provide information about the item's origin, history and ownership.

Although a world populated by bats and e-tags promises to extend computing to almost anything, it does not address one of the biggest hopes for ubiquitous computing—that sensors, effectors and actuators can also be incorporated into devices, making systems capable of both processing information and responding to it. Former PARC director John Seely Brown, for example, foresees a world where millions of networked sensors are placed in roadways, using information about traffic to ease congestion and thereby "harmonize human activity with the environment" (*see "Where Have All the Computers Gone?" p. 86*).

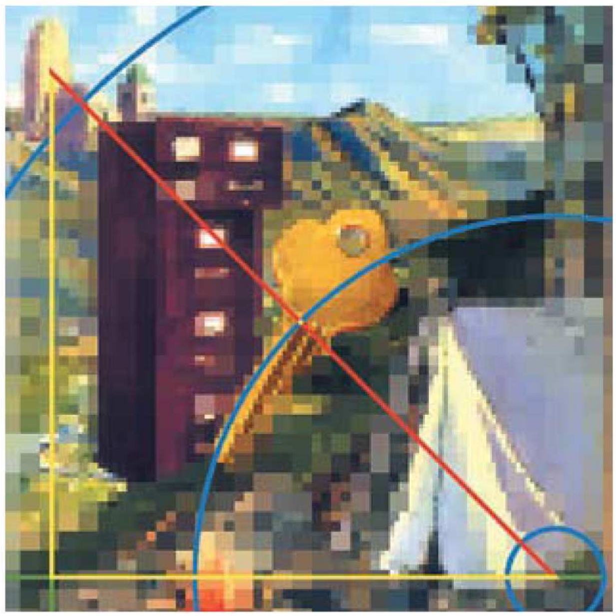
The Digital Companion

While promising to add great utility to people's lives, most context-aware technologies depend on direct communication between humans and a known device or application. In reality, whether at home or on the road, people will also need help tapping services unknown to them—and with which they won't ever want to interact directly.

Enter a third major aspect of ubiquitous computing: software agents, or bots, that root around behind the scenes to find services and generally get things done without bothering humans with the details. Many bots are already on the market, cataloging the Web for Internet portals or tracking customer preferences for e-tailers. But a new generation is at hand. Some

bots are specific to individual devices or applications. Others are more like executive assistants—looking for bargains, negotiating deals and rounding up dozens of services into larger, coordinated actions.

Among the first bots to hit the market could be context-aware applications that seek to prevent information overload by filtering e-mail, phone calls and news alerts. Many firms are tackling this problem. At Microsoft, software agents-under-development make these decisions based on such factors as message content, the kinds of communiqués users read first or delete without opening, and the message writer's relationship with the reader or position in a company organization chart. Agents can then determine whether to interrupt or not by correlating that information—with the help of desktop sensors such as microphones and cameras—with whether the person is on the phone, busy at the keyboard or meeting with someone. If the person is out, the agents can even decide whether to track him or her down via pager or cell phone.



What puts the technology into the futuristic agent class, however, is that it employs procedures based on statistical reasoning techniques in order to draw inferences from users' behavior and make its judgments. The same techniques enable the system to learn from past experiences to get better at its job. Eric Horvitz, leader of Microsoft Research's Adaptive Systems & Interaction group, says he knows firsthand the power of the system, which he has been testing personally—and relying on—for months. Last fall, after leaving work early one Friday afternoon to attend a circus with his family, his cell phone buzzed quietly in his pocket with word of an important e-mail message. "The circus started at 4," he relates, "and at 3:55, I got an urgent note from Bill G. seeking feedback on a memo he was putting together." Horvitz was able to quickly schedule time to review Bill Gates' memo immediately after the event—rather than waiting until Monday.

And that's only an opening salvo in the coming agent wars, as indicated by SRI's car-to-refrigerator demonstration. Explains researcher David Martin, the demo employs a software technology that acts as a superagent—or facilitator—to orchestrate the services of a multitude of other agents. Under this Open Agent Architecture (OAA) framework, humans take no direct hand in controlling the fleet of servants sent scurrying to do their bidding. They merely express their desires to the OAA through a microphone or keyboard, by drawing on a display screen or even speaking over the telephone—and things get done *(see "Open Agent Architecture," p. 58)*.

Even this, though, is merely an appetizer for an idea, still without concrete embodiment, which SRI calls the "digital companion." Much like Microsoft's statistically based filters, it envisions agents that adapt to human needs—only on a much larger scale, as the OAA facilitator idea is extended to include personalized agents that will stay with people for years or even decades. Just as a good secretary learns a boss's preferences and even comes to anticipate his or her needs, so will a digital companion serve its human masters.

"Think of it as a PDA (personal digital assistant) on steroids," relates SRI's Mark. "It is your assistant, it is your broker to this set of services and devices available in the network." Your companion, he says, will authenticate your identity and pay your bills. It will make travel arrangements based on your preferences—and will even see to it that the rental car's radio is set to your desires. Can't remember the wine you drank at a restaurant last week? Just ask your companion: It will reference your bills and maybe the restaurant's wine list to find out. In short, says Mark, a digital companion will be a person's "universal remote for the world."

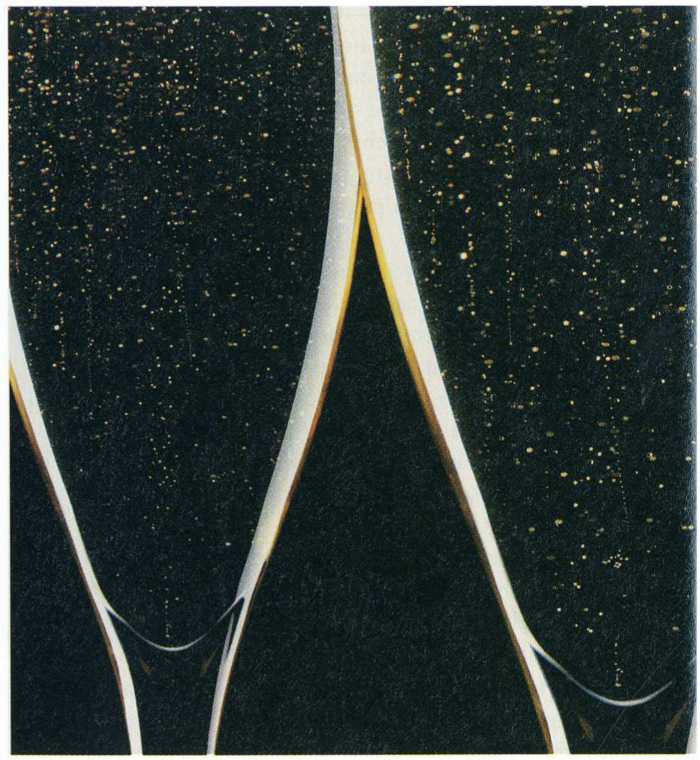
The ubiquitous-computing vision remains in many senses just that: a vision. Beyond the immense technological challenges of building a public utility infrastructure and creating digital companions loom mind-staggering issues that run from programming for the networked world to real fears of Big Brother-like invasions of privacy. Jeffrey Kephart, who heads the Agents and Emerging Phenomena group at IBM's Thomas J. Watson Research Center in Hawthorne, N.Y., even foresees the billions of agents that will soon be out there setting prices, bidding and making purchasing decisions as an economic wild card with potentially immense ramifications. "What we're talking about is the introduction into the economy of a new economic species," he says. "Heretofore we've only had humans." He's working to model and study the dynamics of such a system—and divine ways to avoid price wars and generally help prevent things from getting out of control.

No one yet knows the solution to such puzzles—nor are the answers even evident in today's mishmash of efforts. All of which means that truly ubiquitous computing could still be decades off.

Steadily, though, the major pieces seem to be coming together, giving rise to a view among some in the industry that the new day is at hand. SRI's Mark is one such optimist. So, too, is Jim Waldo, chief engineer of Sun's Jini effort, which, by removing many of the barriers that exist between systems based on different operating systems and languages, marks a big step toward the dream.

"My feeling about the whole ubiquitous computing thing is it's getting to the point of almost being a supersaturated solution—and at some point, the crystal's going to form. And when it does, it's going to happen really fast," Waldo asserts. "There's going to be lots of this base work. It's going to be going nowhere—and all of a sudden it's just going to be there." ◊

dreams made real.

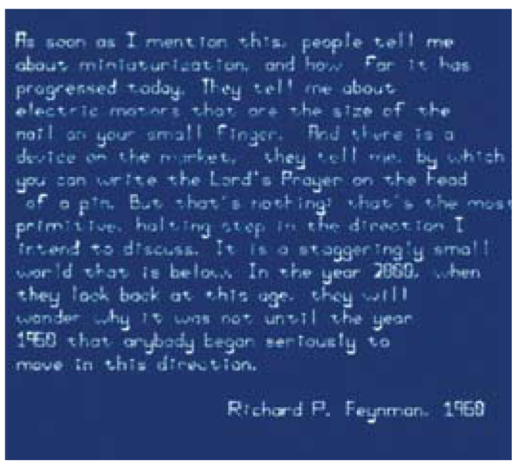


Nanotech GOES TO WORK

DON'T EXPECT MICROSCOPIC ROBOTS ANYTIME SOON. BUT ADVANCES IN MAKING ACTUAL NANOTECH DEVICES ARE PROVING THE VALUE OF WORKING SMALL—REALLY SMALL. THE PAYOFFS WILL COME IN EVERYTHING FROM TINY COMPUTER MEMORIES TO FASTER DNA CHIPS.

BY DAVID ROTMAN

IT'S AN ODD WAY TO DO chemistry. In a small room off his main lab at Northwestern University, Chad Mirkin sits at a personal computer and types. Next to him on the desktop is a plain-looking analytic instrument. Only this is no ordinary piece of lab equipment. It's an atomic force microscope, or AFM, and it's changing the way scientists interact with matter on the very small scale. This particular version of the AFM, specially modified by Mirkin and his co-workers, is about to perform a feat that just a few years ago would have been unthinkable.

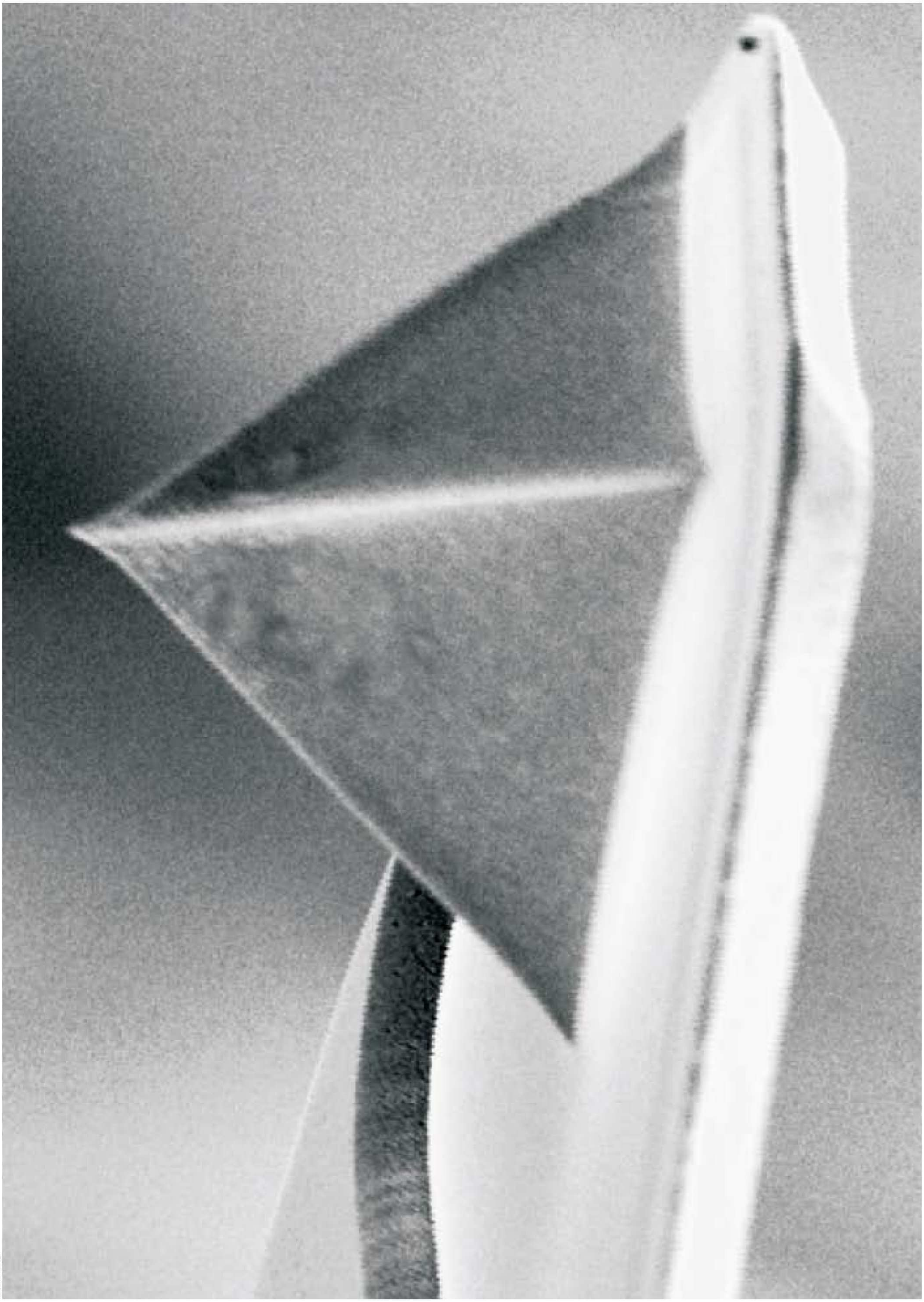


CHAD MIRKIN

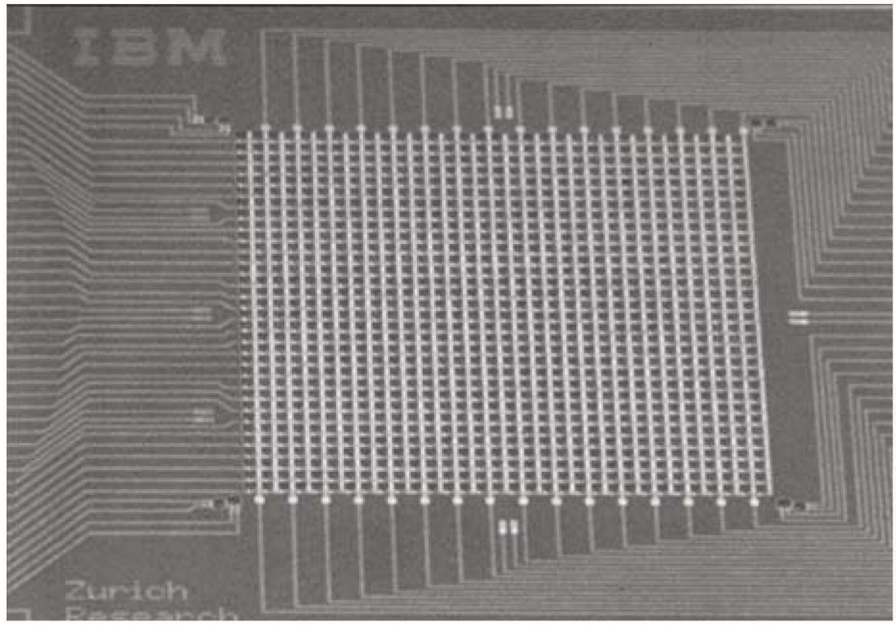
Using an AFM tip (opposite page), Chad Mirkin has written part of Richard Feynman's famous 1960 paper. Each letter is from 60 to several hundred nanometers wide.

Inside a chamber of the AFM, invisible to the naked eye, the tips of tiny probes dip into a well of organic molecules. The microscopic tips, sharpened to a point only a few atoms wide, then "write" the words typed by Mirkin in letters tens to hundreds of nanometers wide (a nanometer is a billionth of a meter). The process works because the organic molecules flow off the probe—just like ink from the point of a fountain pen—via a water droplet that forms on the end of the tip; the molecules then bind to the gold writing surface in orderly fashion. By automating the procedure and rigging up a number of tips in parallel, Mirkin has learned how to use the AFM to rapidly and directly create structures at the nanometer scale. At the magnification required to read the letters, a line from a ballpoint pen would be over a kilometer wide.

It's called "dip-pen nanolithography." But don't think of a fountain pen or even of an antique quill pen—this nano pen isn't for writing, at least not in the familiar sense.



CHAD MIRKIN



IBM's Millipede device for ultradense data storage uses an array of 1,024 AFM tips, each addressed by microelectronics. The entire AFM grid measures 3 millimeters by 3 millimeters.

IBM ZURICH RESEARCH LABORATORY

Using hundreds or even thousands of the probes in parallel, dip-pen lithography could be a quick way to manufacture nano components for everything from microelectronics to faster and denser DNA chips used in genetic screening *(see "DNA Chips," p. 118)*. "This could be much more than a research tool," says Mirkin. "It could be a way to mass-produce nanostructures."

In 1989, physicists at IBM's Almaden Research Center in San Jose, Calif., dazzled the scientific world when they used a microscopic probe to painstakingly move a series of xenon atoms on a nickel surface to form a Lilliputian version of the three letters in Big Blue's logo. While the experiment suggested that it might be possible to build things on the nanoscale, it remained an exotic, one-off trick, requiring a custom-built microscope that filled a small, vibration-damped room and temperatures around –270 C, just a few degrees above absolute zero.

A decade later, Mirkin is turning nano writing into a practical fabrication tool. By incorporating an array of eight tips into a desktop AFM process, Seunghun Hong, a postdoc in Mirkin's lab, recently wrote out a section of a famous 1960 paper by the physicist Richard Feynman predicting the future of nanotechnology. It took Hong less than 10 minutes, and he did it at room temperature. Equally impressive, with Mirkin's technique, one can write using various types of molecules, including biological ones such as DNA, and can readily switch from one "ink" to another. This versatility allows Mirkin to create complex structures. He could, for example, craft an array of thousands of nanostructures, each one consisting of a different type of biological molecule. Such ultradense nano arrays could prove invaluable in discovering new drugs or diagnosing disease.

MIRKIN'S INVENTION, A RAPID AND DIRECT WAY TO MAKE COMPLEX NANOSTRUCTURES, ILLUSTRATES THE PROGRESS NUMEROUS ACADEMIC AND INDUSTRIAL LABS ARE MAKING IN TURNING NANO DOODLINGS INTO REAL TECHNOLOGY.

Mirkin's invention illustrates the rapid progress academic and industrial labs are making in transforming nano doodling into real technology. For many purists, true nanotechnology means building atom-by-atom to make nano machines that operate independently. It's a powerful vision, but it's one that likely remains years away from reality. Meanwhile, a growing number of physicists, chemists and electrical engineers are on the verge of realizing a more practical version of nanotech.

Their ultrasmall structures are a far cry from the "nanobots" (nanoscale robots) and microscopic computers envisioned by some enthusiasts *(see "Nanotechnology: The Hope & The Hype,"* TR *March/April 1999)*. Today's nano devices often consist of hundreds or even millions of atoms and molecules—and they lack the atomic precision that could eventually be possible in nanotechnology. What's more, current nanostructures are frequently just one component in much larger devices. But they have one big advantage over the purists' version: They are real. And though even the most well developed of these nano machines are still probably several years away from being commercially useful, prototypes are already demonstrating the potential role of nanotech in making possible many of tomorrow's most alluring technologies, from pervasive computing *(see "Computing Goes Everywhere," p. 52)* to personalized medicine *(see "Medicine Gets Personal," p. 72)*.

Memory Boost

IF MIRKIN CAN BE DESCRIBED AS A nano scribe, IBM electrical engineer Peter Vettiger is a nano boxer, using AFM tips to punch at a soft polymer surface. Working in the same IBM Research lab in Zurich that helped invent the AFM in 1986, Vettiger and co-workers have built a data storage device that uses an array of 1,024 tiny AFM probes to make indentations in the polymer, each divot "writing" a bit of information no more than 50 nanometers in diameter. The scientists then use the same array of tips to rapidly read the indentations and erase them as needed.

For those pondering the future of information technology, the IBM work is exciting because storing a bit of data at that scale translates into the ability to pack immense amounts of data into a very small area. Today's best storage products (based on magnetic memory) hold about two gigabits per square centimeter, and physicists believe the limit of magnetic memory is around 12 gigabits per square centimeter.

Results from Vettiger's prototype, nicknamed "Millipede," suggest the AFM-based memory could smash those limits. In tests done last year, the IBM

scientists achieved a density of 35 gigabits per square centimeter (up to 80 gigabits per square centimeter using a single AFM tip), reading and writing the information at a speed that rivals existing magnetic devices. Such a density of information could make it possible, by integrating millions of tips together, to produce a hard drive with terabytes of memory—about 40 times greater than what is now commercially available. So far, says Vettiger, there aren't any "show-stoppers" to achieving that vision.

Even more intriguing for those interested in pervasive computing, the technology could mean packing a few gigabytes (enough memory to hold a thousand high-resolution photographs or a thousand 200-page books) onto a device the size of a wristwatch. The advent of ubiquitous computing will create new markets for ultrasmall hard drives, particularly for mobile products such as cell phones and watches. Last summer, for example, IBM introduced a product called Microdrive that packs a gigabyte onto a miniaturized magnetic hard drive roughly the size of a matchbox. But, says Vettiger, the Millipede technology could go far beyond that, making gigabyte hard drives as small as a square centimeter. Equally important, he says, this AFM-based "nanodrive" will require less energy to operate than a magnetic hard drive—a critical factor in portable products.

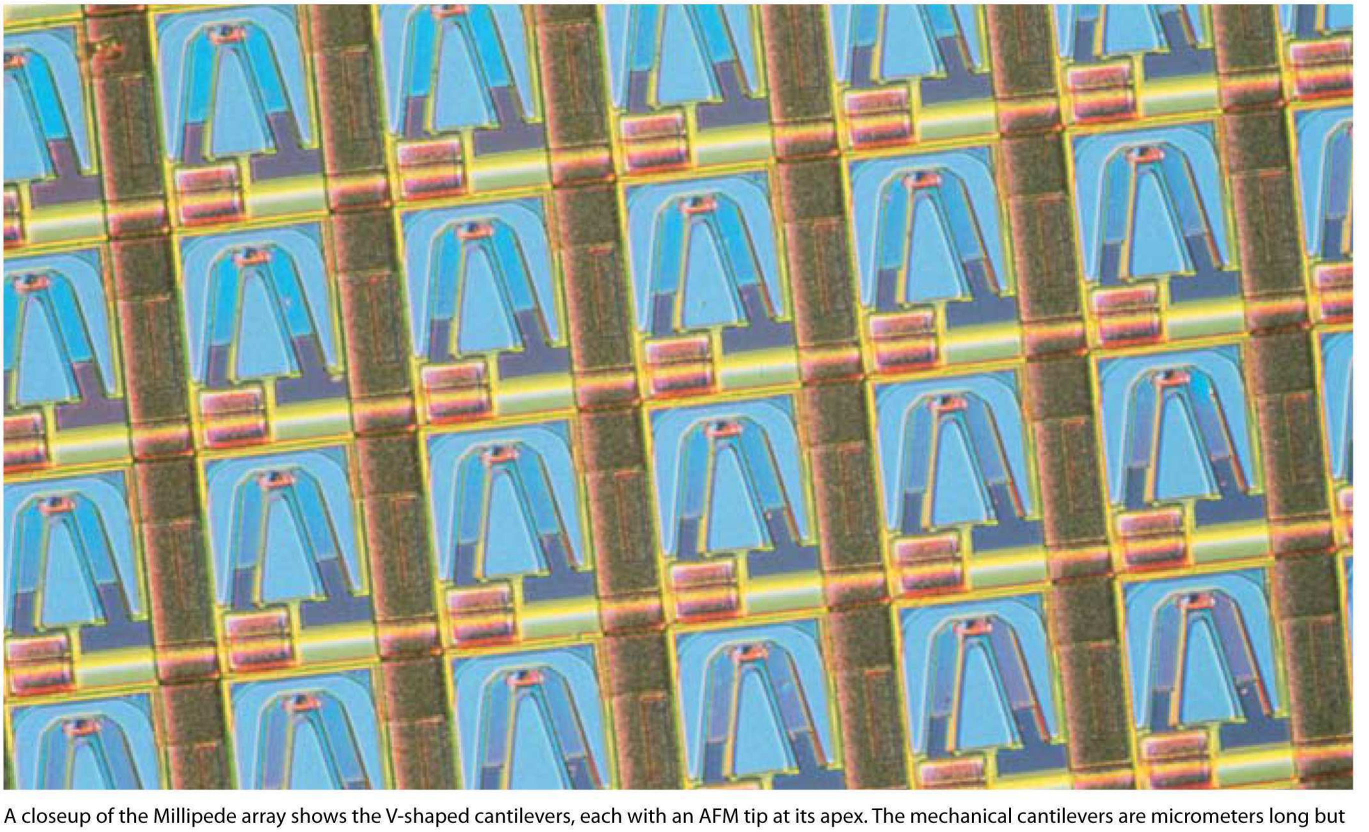
The prospect of watching videos on his wristwatch, however, is not what drives Vettiger. Building the Millipede prototype proved the IBM technologists could integrate a large number of AFM tips with the electronics required to control them—and do it all on a small chip. Millipede is, in effect, a chip in which microelectronics are combined with micromechanics. And, says Vettiger, it could be possible to build a "smart" version of Millipede that intelligently searches its ultradense heap of data for patterns. "You now have millions of transistors on a chip. You can build the same number of mechanical devices on a simple chip, providing functions that electronics can't do," he says. "I'm very confident that in Millipede you're just seeing the tip of the iceberg."

Springs to Life

ONE REASON FOR VETTIGER'S ENTHUsiasm is that mechanical devices can do things electronics can't. Electronics are great for moving information, but with mechanics you can detect physical forces and material properties—such as mass—possibly down to the level of individual molecules. Down the hall from Vettiger, Christoph Gerber, one of the inventors of the AFM, is turning loose his nanomechanical skills on biology in order to do just that.

An AFM's tiny imaging tip is suspended from an ultrathin cantilever; as the tip rides over an atomic or molecular surface, minuscule deflections in the cantilever are measured optically with the help of ultrasmall lasers. These cantilevers are essentially small springs, sensitive enough to measure the nano force from individual atoms. Gerber's idea is to use an array of these cantilevers as simple but extremely sensitive sensors. If you coat one of the cantilevers in the array with, say, a particular sequence of DNA, the complementary strand of DNA will selectively bind to that cantilever. You can then detect the deflection of that cantilever and use the information to measure the presence of that specific sequence of DNA—something that is of enormous value in medical research, disease detection and genetic screening.

Gerber and his co-workers have recently built such a sensor. Consisting of eight cantilevers that are each 500



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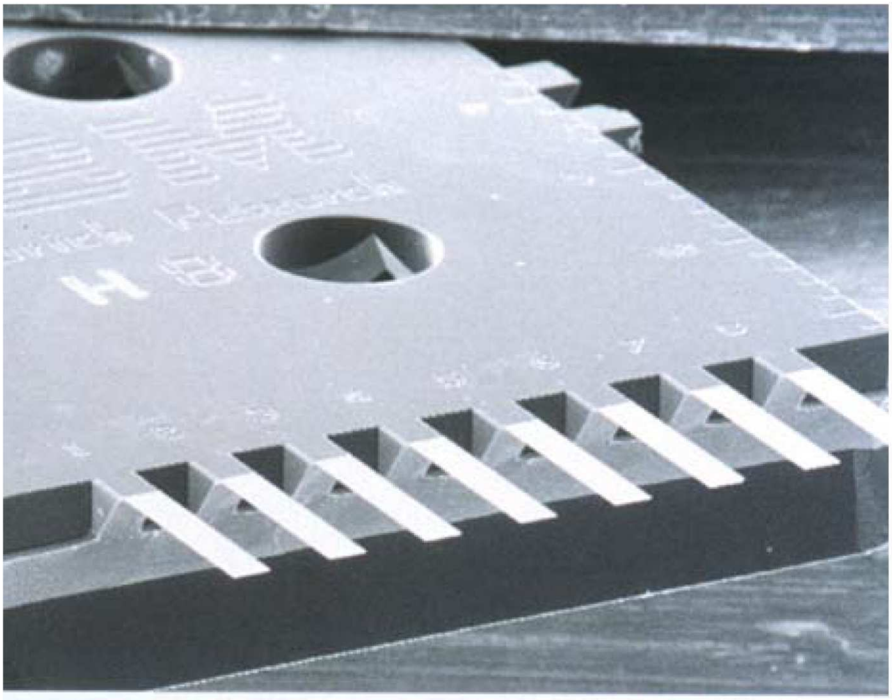
A closeup of the Millipede array shows the V-shaped cantilevers, each with an AFM tip at its apex. The mechanical cantilevers are micrometers long but "punch" divots as small as 50 nanometers in a polymer surface and, subsequently, read those divots as bits.



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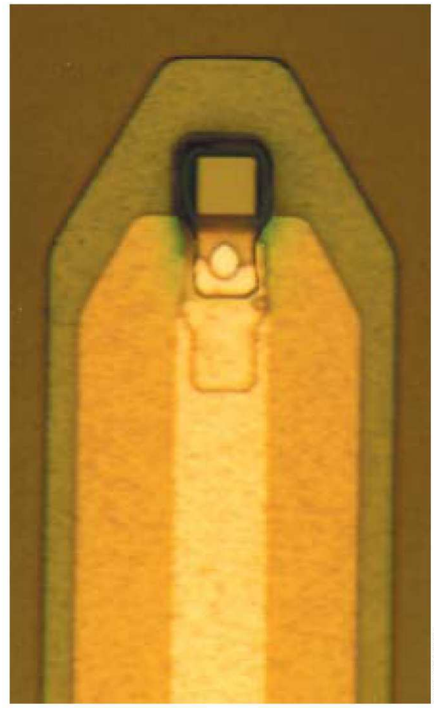

SCOTT MANALIS

Cantilevers designed for AFM probes can serve as effective tools in biological sensing. An IBM Zurich device (left) uses a row of eight cantilevers, each 500 micrometers long, to detect different biological molecules; molecules binding to the cantilevers cause measurable deflections as small as a few nanometers. At MIT's Media Lab, a tiny sensor (right) mounted on a cantilever is small enough to use in microfluidics.

micrometers long but less than one micrometer thick, the device is sensitive enough to measure deflections of only a few nanometers. In recent tests, the sensor differentiated DNA sequences differing by a single base pair (the smallest unit of DNA information); the ability to detect individual base-pair differences without radioactive or fluorescent tags is a remarkable accomplishment. Existing technology for DNA screening—DNA chips—has found wide applications in everything from disease diagnostics to biomedical research; but these commercial chips require the DNA to be fluorescently tagged and read by a bulky optical reader. Gerber believes his biosensors, which don't require tagging of DNA, are potentially far simpler and easier to use.

The cantilever technology could also prove to be a simple way to detect specific proteins, a feat that Gerber says is difficult for current technology. "If we can fully develop this for proteins, we see a great potential," says Gerber. For example, he says, the onset of a heart attack produces in the body a signature set of proteins. However, it often takes hours for physicians to sort out the welter of proteins and determine definitively whether a person is actually having a heart attack. Gerber believes his sensors could quickly and cheaply solve the problem. "We could have a device that says yes or no," predicts Gerber.

Like Vettiger, however, Gerber gets most excited by the longer-term implications of his work. Demonstrating that DNA and protein molecules can actually move a tiny cantilever suggests it might be possible to build nanomachines that act independently. Imagine, Gerber suggests, implanted microcapsules for drug delivery that have a nanoscale valve able to detect a signature protein from a cancer cell; the binding of the protein to the cantilever would trigger the opening of the valve, releasing just the right amount of an anticancer drug from the microcapsule in the exact location needed.

At MIT's Media Lab, Assistant Professor Scott Manalis is using some of the same tools—tiny cantilevers and AFM probes—to tackle similar biological problems. But Manalis is using a completely different strategy: probes that detect electrical signals. Many biological molecules, including DNA and proteins, are electrically charged. But from a materials point of view, the world of biomolecules, which normally exist in a watery environment, is largely incompatible with conventional microelectronics. (Spill water on your Palm Pilot, and you'll get the point.) By altering the makeup of the electronic materials, however, Manalis has fabricated in essence a small transistor at the end of an AFM cantilever that works just fine under water.

The result is a microscopic detector that operates in the environment where DNA, proteins and cells flourish. So far, Manalis and his co-workers are using it as a sensitive probe that can be placed at the end of a microfluidic channel, for example, to detect the electrical signals of—and hence analyze—the DNA flowing out. Like the biosensors being developed at IBM, the tiny device detects DNA without tagging or bulky optical readers. Eventually, Manalis hopes the biosensor could help make possible one of biomedicine's grander visions: a simple wireless device with a few electrodes that could be implanted in a patient with, say, kidney disease to act as an early warning signal detecting when a troublesome protein is being released.

Tiny Tunes

THE RELIANCE ON AFM TIPS AND CANTILEVERS illustrates a decidedly mechanical bent in much of today's nanotech research. Indeed, the strategy of using small silicon-based machines called MEMS (microelectromechanical systems) to manipulate nano devices is turning out to be an espe-

cially promising area. These micromachines are hundreds or thousands of times bigger than the nanoscale and are commercially used in everything from automobile air bags to switches in optical networks. But in the hands of skilled researchers, MEMS can offer a valuable way to control nano action.

In turn, the incorporation of nanoscale structures can greatly increase the utility of existing MEMS technology. "There are a number of situations with devices a few tens or even thousands of micrometers in size where one critical dimension needs to be smaller. Right at the heart of the device you may need a nanoscale feature," says Michael Roukes, a physicist at the California Institute of Technology. Nanomachines are particularly useful in responding to "very feeble forces," says Roukes, who has recently fabricated devices such as a nano resonator, which vibrates like the strings on a tiny guitar. Incorporating these nano devices into MEMS could, for example, yield signal processors that consume minuscule amounts of power.

But the "killer application," says Roukes, could turn out to be a far more sensitive method for magnetic resonance imaging. MRI is widely used by both physicians and scientists to create images of biological structures. Present-day MRI, however, is limited because the technology requires a signal from a large number of molecules. Using an ultrasensitive nano resonator to detect the magnetic signals from a sample, Roukes and his collaborators hope to use the technology to image single biological molecules. That would make it possible, for example, to look at a DNA molecule and directly read its sequences of chemical bases, Roukes says. Almost all the ingredients necessary for a version of MRI with atomic resolution are available, he says, adding that the technology could be ready within five years.

IMPLANTED MICROCAPSULES WITH A NANOMECHANICAL VALVE COULD DETECT A SIGNATURE PROTEIN FROM A CANCER CELL, RELEASING JUST THE RIGHT AMOUNT OF AN ANTICANCER DRUG IN THE EXACT LOCATION WHERE IT IS NEEDED.

Despite the progress, most researchers readily admit these are still the early days of nanotech. Roukes, for one, says his group is making "the Model Ts" of nanomachines. But nanotechnologists also say that new ways of making nano devices are, for the first time, putting into the hands of biologists, physicists and engineers the tools needed to begin to exploit the world of the very small. "We'll see over the next 10 years what we actually can do with these tools," says Mirkin. "But what's exciting is that we're finally getting the technology that allows us to design and build, in a reasonably fast manner, architectures with dimensions from one to 100 nanometers. This is a length scale that, in the past, has been a very difficult place to access."

Challenging, no doubt. But if Mirkin and other nanotechnologists are right, it will be one of the sweet spots of tomorrow's technology. ◊

Old Economy to Nano Economy

For much of his career, Bob G. Gower was a quintessential chemical industry executive. For more than a decade, he ran one of the world's largest petrochemical producers, Houston-based Lyondell Petrochemical, a company that measured its output in hundreds of thousands of metric tons. Now Gower is turning his business ambitions from bulk chemicals to a world where the product is too small to be seen with the naked eye.

In a sign that nanotech is gaining commercial credibility, Gower has co-founded Carbon Nanotechnologies Inc. (CNI) with Richard Smalley, the Rice University chemist who won the 1996 Nobel Prize for the discovery of a new class of carbon called fullerenes. The startup plans to produce and market carbon nanotubes, a form of fullerenes that possesses extraordinary electrical and heat conducting properties. While CNI is not the first startup to enter the fledgling nanotech arena, given the management and scientific pedigrees of its co-founders, it could be the first to have a realistic chance at making nanotech a successful business. "I believe this material [carbon nanotubes] could really change how business is done," says Gower. "It has the potential to change old-economy companies into new-economy businesses."

Nanotubes are pipe-shaped molecules about the size of a DNA double helix. They can be chemically tailored into excellent conductors of heat, conductors (or semiconductors) of electricity, as well as bundled together to form a fiber 100 times stronger than steel. Perhaps most promising is their potential to act as nano wires and even tiny transistors in ultradense integrated circuits. "The most compelling thing about nanotubes is their unparalleled electronic conductivity; they're without peers [among molecules]," says Smalley.

In the short term, says Gower, "one of the most exciting applications" is the use of nanotubes in flat-panel displays that use electron field-emission technology (nanotubes make excellent pipes for the high-energy electrons). Other applications, says Gower, could come in electromagnetic shielding for cell phones and laptops, and in high-strength composites.

For now, CNI will sell the materials to the several hundred research labs working on nanotubes. But, says Gower, the objective is for the company to grow quickly. "We expect to be a profitable operation in the not-too-distant future," he says. CNI's business plan calls for raising up to $10 million this year and another $50 million next year in venture funding. By late 2002, the startup expects to be producing about 10 kilograms of nanotubes per day. And, says Gower, commercial production could reach "a fair number of tons per year by 2004."

That may be tiny compared with the standards of the chemical industry. But then again, the last time anyone checked, petrochemicals like polyethylene were selling for around $800 a metric ton, and carbon nanotubes were going for $1,000 a gram.

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THE OLD WAY—One size of drug fits all.

THE NEW WAY—Each medicine will be adapted to the genetic makeup of individuals or subgroups of the population. THE GOAL—Better treatments, better control of side effects.

BY MARC WORTMAN In early 1999, Karen Cassidy, a dental hygienist and former high school athletics official, saw ads touting the new LYMErix vaccine for preventing Lyme disease, a bacterial infection passed to people by the bloodsucking bite of the deer tick. "Deer are right at my back door," says Cassidy, who hoped the vaccine would let her rake the yard of her suburban Philadelphia home without fear. But shortly after she completed two of a course of three inoculations in May 1999, Cassidy began experiencing burning pain in her back, numbness in her arms and aches and swelling in an ankle. "Just the thought of walking across the yard hurt me," says Cassidy.

By the following December, the pain was so intense she was considering reconstructive surgery for her ankle and had joined over 100 others in a class action lawsuit charging LYMErix's developer, the pharmaceutical giant SmithKline Beecham, with, among other things, ignoring warnings that a genetically identifiable class of recipients—as many as 30 percent of patients—may develop an incurable autoimmune disorder called treatment-resistant Lyme arthritis from the vaccine.

While Cassidy's diagnosis is in dispute, her legal case is an undeniable indicator of how dramatically medicine is being transformed by a new science known as pharmacogenomics. ILLUSTRATIONS BY STUART BRADFORD

Medicine Gets Personal


Dorsal Cavity
a. Orbital cavity
b. Nasal cavity
c. Buccal cavity
d. Thoracic cavity
The Diaphragm
thoracic and abdom
e. Abdominal cavity
f. Pelvic cavity
HUMAN BODY
Ventral Cavity
treatment
tests made in diagnosis and treatment
C U S T O M F I T

Now that the Human Genome Project is largely complete, academics and companies are shifting their emphasis to the study of how genes vary among people. The Human Genome Project involves decoding the sequence of one complete set of human genes, a kind of genetic Everyman. But that template won't describe everyone, since DNA varies slightly from person to person. And those minute variations in the DNA, scientists believe, may determine which patients will benefit most from particular drugs—as well as which subgroups may be harmed by them.

That's the idea of pharmacogenomics, and it is taking the drug industry by storm. The term, coined only four years ago, now encompasses the aspirations of a large number of enterprising biotechnology companies and academic laboratories. This is an era of transition in medicine: from the time of "one size fits all" drugs created for and marketed to all patients, to the emerging epoch of personalized medicines, in which drugs are geared to the specific genetic makeup of groups or individuals. This transition is causing growing pains for some companies. But the ultimate payoff, a decade or more away, should be enormously beneficial to patients, enabling doctors to think about stopping tumors before they begin and heart attacks before they happen.

"This is not a fad," says Gualberto Ruano, CEO of Genaissance Pharmaceuticals in New Haven, Conn., a player in the transition. "It's a major tidal wave changing the entire pattern of health care." And Alan Roses, who leads genetics research at drug giant Glaxo Wellcome in Research Triangle Park, N.C., agrees wholeheartedly that pharmacogenomics "is a disruptive technology, not a technology that sustains what organizations are used to doing. It's going to be a part of everybody's business, and that's what most people don't seem to understand."

The ULTIMATE PAYOFF will be the ability of physicians to stop tumors before they begin and heart attacks BEFORE they happen.

The DNA Differential

What will the fully realized pharmacogenomics revolution in medicine bring us? Numerous questions involving health insurance and other nagging ethical, political and social issues must be confronted over the next decade *(see "Yourgenome.com," p. 78)*. But eventually knowledge of the relevant variations in your own genome—perhaps via a readout in your doctor's office using a biochip—will provide predictions of your potential health problems before they happen. To start with, there will be indications of whether a particular medication might have toxic side effects for you, based on your DNA. Then there will be prescriptions specifying which of the many pharmaceutical and other health care options will be optimal for you. Finally, physicians will be armed with genetically targeted medications, advice for behavior change and other elements of what Nicholas Dracopoli, executive director of the Pharmacogenomics and Human Genetics Group at Bristol-Myers Squibb, calls "disease management packages." This will allow doctors to intervene well in advance of symptoms, so tumors won't form, arteries won't clog, bones won't grow brittle and aging brain cells won't die.

Before we reach this payoff, several key technological challenges must be overcome (*see "Breakthroughs Ahead," p. 75*). The first is to identify as many of the small genetic variations between individuals as possible. These variations, known as single nucleotide polymorphisms (SNPs), are simple chemical substitutions of one letter of the DNA alphabet for another in a person's genes; though "minute," these substitutions can make a world of difference in how a person responds to a given medication. Yet not all SNPs actually have much medical significance, and sorting out the important from the unimportant is another crucial technological challenge.

Sidestepping Side Effects

Even before these technological problems are conclusively solved, the first steps toward personalized medicine are already being taken. Indeed, two waves of innovation are likely before the full array of "disease management packages" is in place. The first wave includes genetic tests to predict which patients will suffer "adverse reactions," the sometimes fatal side effects caused by drugs.

One test for such differences is already saving lives: a genetic screen developed by St. Jude Children's Research Hospital in Memphis, Tenn., for mutations in the thiopurine S-methyltransferase (TPMT) gene. TPMT regulates how the liver breaks down certain drugs, including 6-mercaptopurine, a chemical that's a lifesaver for victims of acute lymphoblastic leukemia, a deadly form of cancer that afflicts approximately 2,400 American children and adolescents each year, according to the National Cancer Institute. Between 10 and 15 percent of children metabolize the drug either too quickly or too slowly. The former don't gain a benefit from a standard dose, while the latter can accumulate lethal levels of the drug.

Although the TPMT test is now being used to choose the right drug dosage, few treatments have such tests. For instance, there's no routine testing before giving chemotherapy for most other cancers. Patricia Rodriguez, a hematology oncologist at Arlington-Fairfax Hematology-Oncology Group in Arlington, Va., says, "You know the drugs are going to be toxic, but sometimes there are idiosyncratic side effects, and you can't predict who is going to have them. When it happens, it's terrible."

Although developing tests that predict side effects seems like a commonsense proposition, in fact it runs counter to almost every conventional notion of how drugs are developed and marketed. The pharmaceutical industry wants single drugs that work safely for everybody (*see "Pharma's Blockbuster Habit,"* TR *July/August 2000*). Of course, most drugs don't. And now that genetics is providing some insights as to why, the "one size fits all" attitude is becoming more and more out of tune with reality—sometimes dangerously so.

Despite safety study and clinical trial protocols that typically involve many thousands of patients and five or more years of testing, drugs causing serious, unpredicted side effects do make it through to FDA approval and the marketplace. According to a 1998 study published in *Journal of the American Medical Association*, an estimat-

ed 2.2 million patients had adverse reactions to drugs in 1994, and 106,000 patients died. Adverse drug reactions are by some estimates the fourth leading cause of death in America.

According to Dale Pfost, president and CEO of the Princeton, N.J.-based Orchid BioSciences, a company developing SNP technologies, the pharmaceuticals industry has an unpleasant secret: "More money is spent on adverse drug response than on drug development."

Safety First

The pharmacogenomics revolution has a chance to change this picture. Within five years, genetic tests identifying individuals at risk for an adverse reaction will very likely be a more routine part of how new drugs are developed; after that, such tests may actually be co-marketed with new drugs.

Taking the lead are companies like Glaxo Wellcome, which will soon merge with SmithKline Beecham. Glaxo signaled its commitment to the area by hiring pharmacogenomics pioneer Roses in 1997 to lead its gene research efforts. As director of the Center for Human Genetics at Duke University, Roses had a hand in tracking down the gene that causes amyotrophic lateral sclerosis (Lou Gehrig's disease) and led the team that identified apolipoprotein E (apoE), a major genetic factor in Alzheimer's disease.

Roses has set up a widespread network of medical-center-based programs to speed the search for disease genes. One of the first successes was creating a map of the SNPs present in the apoE gene; this development has opened up an entire new frontier in searching out genetically targeted treatments for Alzheimer's, which has proved notoriously hard to treat.

While developing a more effective Alzheimer's drug could take a decade, Roses expects in the next two to five years to submit for FDA approval a pharmacogenetic test for the safety of Glaxo's anti-HIV drug Ziagen. Around 5 percent of AIDS patients have a predisposition to develop dangerous and potentially fatal hypersensitivity reactions to this medication, a rate found with other AIDS drugs as well. If the FDA approves the test, then the right 5 percent of the population will know not to take Ziagen.

That test, Roses says, will be the "proof of principle" that the genetic revolution is both smart business and good for people. He contends it will "have a revolutionary effect on the pharmaceutical industry," dramatically changing the way the industry operates. "It will be inescapable. You cannot deny evidence-based safety testing to people taking a drug."

Many of Roses' peers worry that pharmacogenomics may fragment their markets in ways that could be lethal to the corporate bottom line. Roses believes otherwise, arguing that the new Ziagen test will drive far more people to Glaxo's drug. Armed with pharmacogenetic tests for safety, he says, Glaxo's products will have "...a huge competitive advantage.... Would you pay more for a pill that is a thousand times safer?" And once that first test for Ziagen demonstrates its market, "the dominoes will start to fall," he says. "Consumers will

Breakthroughs Ahead

Biotech and drug firms are competing fiercely to bring together several technologies needed to make the pharmacogenomics vision a reality (see "The SNPs Factor," p. 76). Dozens of biotechnology companies, including Celera Genomics in Rockville, Md., Millennium Pharmaceuticals in Cambridge, Mass., CuraGen in New Haven, Conn., and Genaissance Pharmaceuticals in New Haven are now racing to discover genetic differences between people known as single nucleotide polymorphisms—so-called SNPs (pronounced "snips"). SNPs are the most common type of DNA variation, simple chemical substitutions estimated to occur about once in every 1,000 letters of DNA code. Although SNPs amount to less than 0.1 percent of the genome, they are believed to play a dominant role in determining how human beings differ from each other functionally.

Identifying SNPs is considered so fundamental for the future of genetically based medicine that 13 normally cutthroat pharmaceutical competitors, along with Britain's Wellcome Trust, banded together in early 1999 to form the Chicago-based SNP Consortium, an international multicenter effort much like the Human Genome Project, to map SNPs and post them on the Internet for unrestricted public access. The consortium, now wrapping up its work, has found approximately 1 million SNPs, and Celera's SNP Reference Database contains 2.8 million. Estimates of the total number of SNPs range up to 30 million, but not all SNPs are of equal value. There are likely to be far fewer—some guess in the low thousands—that account for the genetic contribution to virtually all aspects of our potential health outcomes, from how we metabolize drugs, to the pace of aging, to our cells' susceptibility to cancer.

Discovering just which SNPs matter will require the participation of huge numbers of patients now being recruited to provide both DNA samples and detailed health histories. And figuring out how to protect this sensitive data while allowing scientists the access they need is giving ethics and privacy experts plenty to think about.

As the lawyers, ethicists and consumers struggle with privacy issues, the technologists will be attempting to compare complex clinical variables against thousands of SNP data points—a project that will require enormous advances in efficiency. Identifying one person's version of just one SNP currently costs about $1, an impractical figure given that scientists would like to study tens of thousands of SNPs for each individual. Nicholas Dracopoli, executive director of pharmacogenomics and human genetics at Bristol-Myers Squibb, says, "The current cost of scoring SNPs is way too expensive to utilize large numbers. You need a large cost reduction to move forward in a cost-effective, high-throughput manner." That need has prompted an intense technological race to develop high-throughput SNP "scoring" methods. The race is led by companies such as DNA-chip pioneer Affymetrix of Santa Clara, Calif., and San Diego's Sequenom, a specialist in mass spectrometry. Industry analysts predict costs will drop to pennies per SNP before 2005.

want it. We're a regulated industry. Regulators will demand it."

Targeted Medicine

If the first wave of the pharmacogenomics revolution is already under way—using genetic data to avoid adverse reactions—a second wave is ready to break right behind it: using genetic information to find out which medicines will work optimally for which patients. A Sweden-based firm, Gemini Genomics AB, offers an assay approved for use in Sweden that identifies a subgroup (30 percent) of hypertensive patients who should be treated with angiotensin-converting enzyme (ACE) inhibitors. ACE inhibitors are the most widely used of several different types of hypertension treatments. When they're effective, they save lives. They don't work for many people, though, and cost a great deal, so knowing who would benefit would be a significant advantage to doctors.

Other pharmacogenetic tests for heart disease will soon reach the U.S. market. University of Cincinnati scientist Steve Liggett, a leading pharmacogenomics researcher, has found SNP markers to identify heart patients most likely to experience rapid decline in cardiac function. Once identified, they can be moved up the list for more radical interventions and prioritized for heart transplant. Given that about 4.6 million people in the United States have suffered congestive heart failure according to the American Heart Association, "the ramifications" of such a test, says Liggett, "are enormous."

In her own practice, oncologist Rodriguez is already seeing how the first wave of testing for tumor genes for certain forms of breast cancer and lymphoma has helped her patients. "More targeted therapies are becoming available. That's the direction for the future in which you'll choose more-selective drugs based on genetic material of the tumor cells."

Although the first two waves of pharmacogenomics are already making an impact, it will be a while—a decade or more—before the full payoff comes. One reason is that genes don't provide all the answers for treating disease. Rather, our genes work in concert with behavioral choices, such as cigarette smoking, exercise, diet and environmental exposure, to determine which illnesses we get. Sorting all of that out will be immensely complex. "Drug metabolism is pretty straightforward," says Rick Sheridan, a vice president of PPGx, a pharmacogenomics testing firm in Morrisville, N.C. "These areas are far more subtle. When you get into things like disease predisposition, the frequency of SNP markers may be quite high, but you have to account for environmental triggers that affect almost everything about disease."

To gather the information needed to unravel the puzzle, governments and enterprising companies have begun combing through epidemiologic and public health information collected over the years. For instance, the startup Framingham Genomic Medicine in Framingham, Mass., was recently formed to take advantage of more than 50 years and thousands

The SNPs Factor

DETECTING SNPS

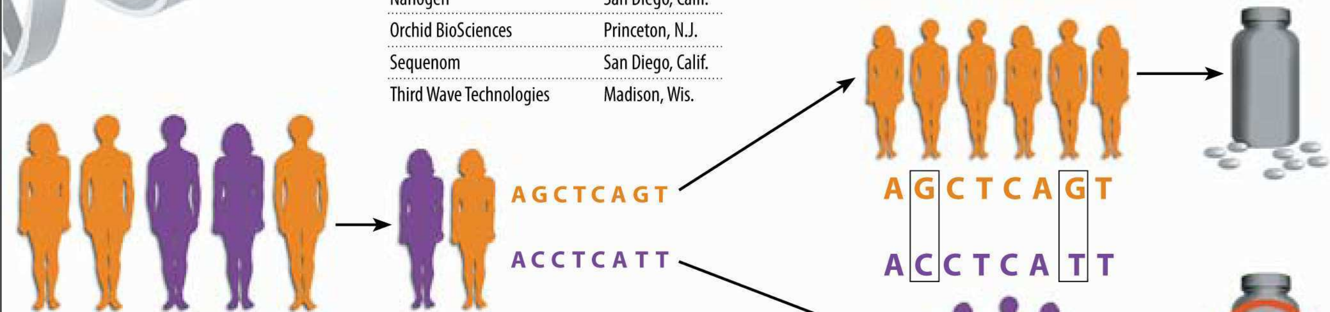
SNP profiles for every patient means reading out thousands or millions of SNPs and requires high-speed DNA detection technology.

Affymetrix	Santa Clara, Calif.
Hyseq	Sunnyvale, Calif.
Nanogen	San Diego, Calif.
Orchid BioSciences	Princeton, N.J.
Sequenom	San Diego, Calif.
Third Wave Technologies	Madison, Wis.

FINDING ASSOCIATIONS

Combining the SNP maps and rapid DNA detection technology will provide readouts of individual genetic profiles.

Genaissance Pharmaceuticals	New Haven, Conn.
Glaxo Wellcome	Research Triangle Park, N.C.
Millennium Pharmaceuticals	Cambridge, Mass.
Variagenics	Cambridge, Mass.



BUILDING DATABASES AND BANKING GENOMES

Databases of patients' health histories and DNA samples are the raw material for pharmacogenomics research.

First Genetic Trust	Chicago, Ill.
deCODE Genetics	Reykjavik, Iceland
DNA Sciences	Mountain View, Calif.
Framingham Genomic Medicine	Framingham, Mass.
Gemini Genomics	Cambridge, U.K.

FINDING THE SNPS

Scientists are developing comprehensive catalogs of the most common type of genetic differences between people, called single nucleotide polymorphisms, or SNPs.

Celera Genomics	Rockville, Md.
Incyte Genomics	Palo Alto, Calif.
National Institutes of Health	Bethesda, Md.
SNP Consortium	Chicago, Ill.

INDIVIDUALIZED MEDICINE

In the future, a doctor may provide a genetic test before prescribing a drug. Only patients able to benefit from a drug will receive it.

BETSY HAYES

of subjects' worth of data collected from the studies first begun as the famous Framingham Heart Study—in which smoking was first linked to heart disease and the notion of "risk factors" was developed. "We're looking for gene-environment interaction," says Fred Ledley, chief scientific officer for Framingham Genomic Medicine. "Good genetic information has to be linked to good clinical data."

Karen Cassidy's case is a good example of how complicated the interactions between our genes, our environment and the drugs we take can be. Was her illness caused by a tick bite, the LYMErix vaccine, some underlying problem in her immune system—or a combination of all three? Today, it is up to the lawyers to sort it all out. But sometime soon clear scientific answers may be possible, not just to resolve health mysteries like Cassidy's, but to prevent them altogether.

When those answers are available, they will do far more than just prevent adverse reactions. They will make it possible to practice medicine in a whole new way. At Genaissance, Ruano's scientific staff is studying patients taking one of the many cholesterol-lowering drugs currently on the market, such as Lipitor, a popular prescription drug that rakes in nearly $4 billion a year in sales. Clinical data showing whose cholesterol drops and whose doesn't, and who has a bad reaction to a drug, is correlated with DNA samples collected from the patients and decoded in the bank of sequencers. The hoped-for outcome: genetic markers that allow the optimal matching of patient and drug.

Armed with the data, a small army of Genaissance software developers are busy writing code for what Ruano hopes will be the "operating system" for the new era of personalized health care—a future in which a doctor seeing a high cholesterol reading, rather than writing a prescription solely on the basis of her accumulated experience, will check your DNA against an online gene database to find the right drug to prescribe.

But isn't that a big change in the doctor's role? Yes, says Herbert Chase, Yale Medical School's deputy dean for education, and the reason is the explosion of medical information. In the future, says Chase, "it is likely that we will know from a drop of blood that a patient has 14 of 19 genes for high blood pressure, and we have 172 drugs that will interact with that. Only a computer will be able to organize this information." Your doctor will become a middleman, Chase suggests, mediating between you, various genomic and information technology systems that will be the backbone of the health care system, and the pharmaceutical treatments that the computer prescribes.

By the time such systems arrive, the current dominant notion that "one size fits all" will likely be a distant memory, having given way to a nuanced, personalized strategy in which health care is focused on finding the right drug for smaller, genetically differentiated segments of the population—even single individuals. For the pharmaceutical industry, it will be a big change. "It's a different mentality," says Genaissance's Ruano. "You need to develop drugs on a smart basis for a targeted market and create a portfolio of drugs that add up to a blockbuster. There will be many more products, and the dynamics of drug development, submission for approval and marketing will have to change." For all who suffer from disease—and sooner or later that's all of us—the changes could be even bigger and more fruitful. ◊

Yourgenome.com

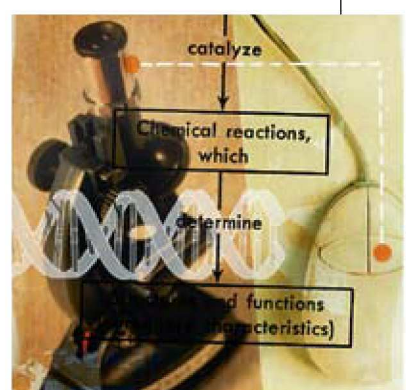
Personalized medicine may still be in its infancy, but the first consumer products linking genetics to health will soon be sold in a drugstore near you and, not surprisingly, also on the Web.

The genetics research firm PPGx, of Morrisville, N.C., plans to sell a home test kit through drugstores and supermarkets that will tell you whether you belong to the 7 to 10 percent of the population whose bodies can't properly metabolize up to one-quarter of all drugs on the market, including many everyday painkillers and cough medicines and even some antidepressants. "If you're a poor metabolizer" taking codeine, says Rick Sheridan, a vice president with PPGx, "you'd get none of the pain-killing benefits, but you'd get the side effects."

The difference lies in a gene called 2D6, part of a family of genes that code for enzymes active in the liver. After sending the company a cheek swab—along with some personal health history—your DNA results will be posted on a secure Web site.

PPGx probably won't make much money on the service, which will likely cost around $20. But the main reason genetics companies want your eyeballs focused on their Web sites is that they think gathering and selling information about your genes and health will be big business. Those databases of DNA samples and health information could help companies discover new drugs and develop safety and efficacy tests for drugs already on the market. PPGx hopes to establish itself as an Internet-based clearinghouse for the expanding world of personalized medicine. "It's an opportunity to be one of the first companies dealing directly with consumers in this area," says Sheridan.

Perhaps the first, but certainly not the last. Last August, DNA Sciences, a Mountain View, Calif., company that counts among its directors Jim Clark, co-founder of Netscape and Silicon Graphics, launched the Gene Trust Project (www.dna.com)—inviting volunteers to submit DNA samples and family and health information that will be used by DNA Sciences for genetic research projects.



That's just the beginning. As scientific studies begin uncovering more and more links between genes, drugs and health, the Internet will also become the place where patients turn to get information about themselves. "There are 30 to 40 important genetic tests today," says Fred Ledley, chief scientific officer of Framingham Genomic Medicine, a company that is mining health data gathered over the past 50 years from people living in Framingham, Mass. And the number will increase, he says. He thinks consumers, wary of letting employers, physicians and insurance companies know their genetic state, will use the Internet to bypass the medical system. "Traditional ways of getting information to consumers won't work," says Ledley. "The intimacy and anonymity of the Web make it especially well suited for getting private health information."

In our September issue, Michael Dertouzos wrote a column, "Not by Reason Alone" (see www.technologyreview.com/articles/oct00/dertouzos.htm), that took Bill Joy of Sun Microsystems to task for a piece Joy had written in *Wired*. In his *Wired* article, Joy argued that humanity should renounce certain lines of research, including nanotechnology, because of the dangers they pose. Dertouzos argued that Joy's view was flawed because his predictions were based on reason which, taken alone, is an inadequate guide to the future. Dertouzos' column drew an impassioned response from Ray Kurzweil, author of *The Age of Spiritual Machines*. We print Kurzweil's letter and Dertouzos' rejoinder.

Kurzweil vs. Dertouzos

Ray Kurzweil

ALTHOUGH I AGREE WITH MICHAEL DERTOUZOS' CONCLUSION IN rejecting Bill Joy's prescription to relinquish "our pursuit of certain kinds of knowledge," I come to this view through a very different route. Although I am often paired with Bill Joy as the technology optimist versus Bill's pessimism, I do share his concerns about the dangers of self-replicating technologies. Michael is being shortsighted in his skepticism.

Michael writes that "just because chips…are getting faster doesn't mean they'll get smarter, let alone lead to self-replication." First of all, machines are already "getting smarter." As just one of many contemporary examples, I've recently held conversations with a person who speaks only German by translating my English speech in real time into human-sounding German speech (by combining speech recognition, language translation and speech synthesis) and similarly converting their spoken German replies into English speech. Although not perfect, this capability was not feasible at all just a few years ago. The intelligence of our technology does not need to be at human levels to be dangerous. Second, the implication that self-replication is harder than intelligence is not accurate. Software viruses, although not very intelligent, are self-replicating as well as being potentially destructive. Bioengineered biological viruses are not far behind. As

PHOTOGRAPH BY WEBB CHAPPELL

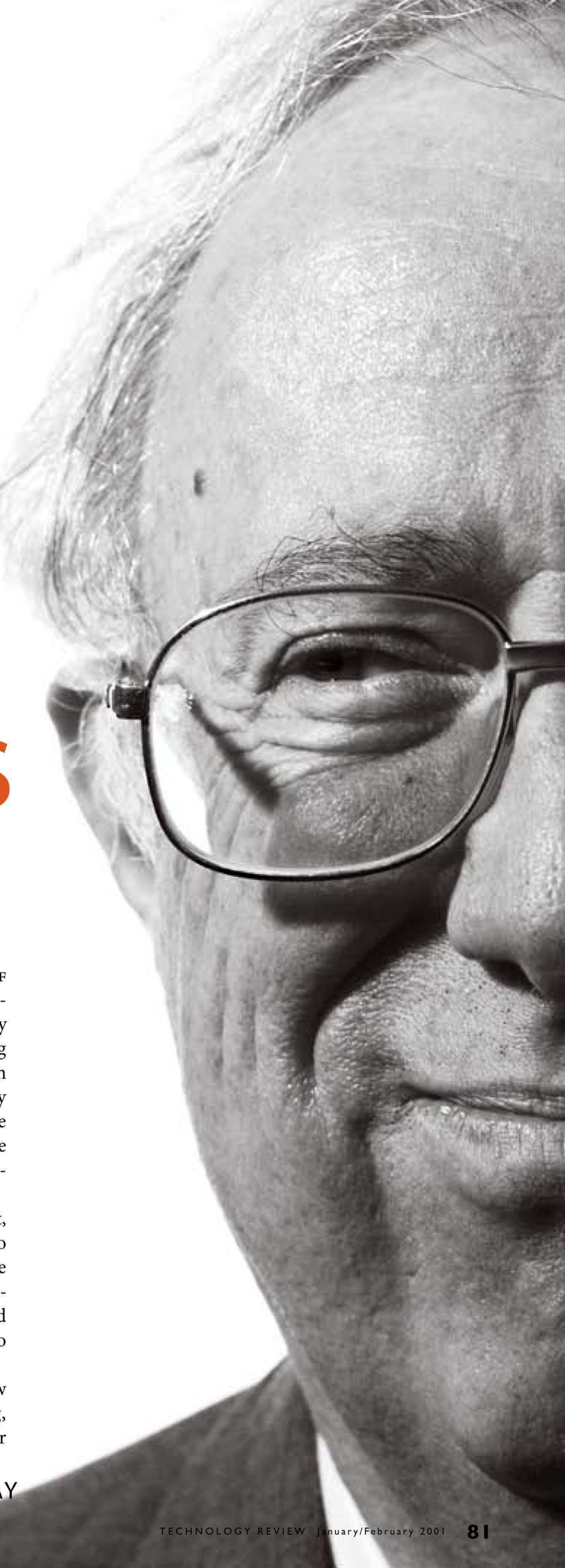
Michael Dertouzos

IN MY COLUMN, I OBSERVED THAT WE HAVE BEEN INCAPABLE OF judging where technologies are headed, hence we should not relinquish a new technology, based strictly on reason. Ray agrees with my conclusion, but for a different reason: He sees technology growing exponentially, thereby offering us the opportunity to alleviate human distress and hasten future economic gains. From his perspective, my point is "irrelevant," and my views on the future of technology are "skeptical." Let's punch through to the underlying issues, which are vital, for they point at a fundamental and all-too-often ignored relationship between technology and humanity.

Ray's exponential-growth argument is half the story: No doubt, the number of transistors on a chip has grown and will continue to grow for a while. But transistors and the systems made with them are used by people. And that's where exponential change stops! Has word-processing software, running on millions of transistors, empowered humans to contribute better writings than Socrates, Descartes or Lao Tzu?

Technologies have undergone dramatic change in the last few centuries. But people's basic needs for food, shelter, nurturing, procreation and survival have not changed in thousands of years. Nor

PHOTOGRAPH BY FURNALD/GRAY



Ray Kurzweil

for nanotechnology-based self-replication, that's further out, but the consensus in that community is this will be feasible in the 2020s, if not sooner.

Many long-range forecasts of technical feasibility in future time periods dramatically underestimate the power of future technology because they are based on what I call the "intuitive linear" view of technological progress rather than the "historical exponential" view. When people think of a future period, they intuitively assume that the current rate of progress will continue for the period being considered. However, careful consideration of the pace of technology shows that the rate of progress is not constant, but it is human nature to adapt to the changing pace, so the intuitive view is that the pace will continue at the current rate. It is typical, therefore, that even sophisticated commentators, when considering the future, extrapolate the current pace of change over the next 10 years or 100 years to determine their expectations. This is why I call this way of looking at the future the "intuitive linear" view.

But any serious consideration of the history of technology shows that technological change is at least exponential, not linear. There are a great many examples of this, including exponential trends in computation, communication, brain scanning, miniaturization and multiple aspects of biotechnology. One can examine this data in many different ways, on many different time scales and for a wide variety of different phenomena, and we find (at least) double exponential growth, a phenomenon I call the "law of accelerating returns." The law of accelerating returns does not rely on an assumption of the continuation of Moore's law, but is based on a rich model of diverse technological processes. What it clearly shows is that technology, particularly the pace of technological change, advances (at least) exponentially, not linearly, and has been doing so since the advent of technology. That is why people tend to overestimate what can be achieved

EVEN THE TECHNO-SAVVY OVERLOOK TECHNOLOGY'S EXPONENTIAL GROWTH RATES.

–Kurzweil

details) but underestimate what can be achieved in the long term (because exponential growth is ignored).

This observation also applies to paradigm shift rates, which are currently doubling (approximately) every decade. So the technological progress in the 21st century will be equivalent to what would require (in the linear view) on the order of 20,000 years.

Michael's argument that we cannot always anticipate the effects of a particular technology is irrelevant here. These exponential trends in computation and communication technologies are greatly empowering the individual. Of course, that's good news in many ways. These trends are behind the pervasive trend we see towards democratization, and are reshaping power relations at all levels of society. But these technologies are also empowering and amplifying our destructive impulses. It's not necessary to anticipate all of the ultimate uses of a technology to see that there is danger in, for example, every

Michael Dertouzos

has the rapid growth of technology altered love, hate, spirituality or the building and destruction of human relationships. Granted, when we are in the frying pan, surrounded by the sizzling oil of rapidly changing technologies, we feel that everything around us is accelerating. But, from the longer range perspective of human history and evolution, change is far more gradual. The novelty of our modern tools is counterbalanced by the constancy of our ancient needs.

As a result, technological growth, regardless of its magnitude, does not automatically empower us. It does so only when it matches our ability to use it for human purposes. And that doesn't happen as often as we'd like. Just think of the growing millions of AIDS cases in Africa, beyond our control. Or, in the industrial world, ask yourself whether we are truly better off surrounded by hordes of complex digital devices that force us to serve them rather than the other way around.

Our humanity meets technology in other ways, too: In forecasting the future of technology, Ray laments that most people use "linear thinking" that builds on existing patterns, thereby missing the big "nonlinear" ideas that are the true drivers of change. Once again, this is only half the story: In the last three decades, as I witnessed the new ideas and the 50-some startups that arose from the MIT Laboratory for Computer Science, I observed a pattern: Every successful technological innovation is the result of two simultaneous forces—a controlled insanity needed to break away from the stranglehold of current reason and ideas, and a disciplined assessment of potential human utility, to filter out the truly absurd. Focusing only on the wild part is not enough: Without a check, it often leads to exhibitionistic thinking, calculated to shock. Wild ideas can be great. But I draw a hard line when such ideas are paraded in front of a lay population as inevitable, or even likely.

That is the case with much of the futurology in today's media, because of the high value we all place on entertainment. With all the talk about intelligent agents, most people think they can go buy them in the corner drugstore. Ray, too, brings up his experience with speech translation to demonstrate computer intelligence. The Lab for Computer Science is delightfully full of Victor Zue's celebrated systems that can understand spoken ish, Spanish and Mandarin, as long as the context is restricted, for example to let you ask about the weather, or to book an airline flight. Does that make them intelligent? No. Conventionally, "intelligence" is centered on our ability to reason, even imperfectly, using common sense. If we dub as intelligent, often for marketing or wishful-thinking purposes, every technological advance that mimics a tiny corner of human behavior, we will be distorting our language and exaggerating the virtues of our technology. We have no basis today to assert that machine intelligence will or will not be achieved. Stating that it will go one way or the other is to assert a belief, which is fine, as long as we say so. Does this mean that machine intelligence will never be achieved? Certainly not. Does it mean that it will be achieved? Certainly not. All it means is that we don't know—an exciting proposition that motivates us to go find out.

Attention-seizing, outlandish ideas are easy and fun to concoct. Far more difficult is to pick future directions that are

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college biotechnology lab having the ability to create self-replicating biological pathogens.

However, I do reject Joy's call for relinquishment of broad areas of technology (such as nanotechnology) despite my not sharing Michael's skepticism on the feasibility of these technologies. Technology has always been a double-edged sword. We don't need to look any further than today's technology to see this. If we imagine describing the dangers that exist today (enough nuclear explosive power to destroy all mammalian life, just for starters) to people who lived a couple of hundred years ago, they would think it mad to take such risks. On the other hand, how many people in the year 2001 would really want to go back to the short, brutish, disease-filled, poverty-stricken, disaster-prone lives that 99 percent of the human race struggled through a couple of centuries ago?

People often go through three stages in examining the impact of future technology: awe and wonderment at its potential to overcome age-old problems, then a sense of dread at a new set of grave dangers that accompany these new technologies, followed, finally and hopefully, by the realization that the only viable and responsible path is to set a careful course that can realize the promise while managing the peril.

The continued opportunity to alleviate human distress is one important motivation for continuing technological advancement. Also compelling are the already apparent economic gains, which will continue to hasten in the decades ahead. There is an insistent economic imperative to continue technological progress: relinquishing technological advancement would be economic suicide for individuals, companies and nations.

Which brings us to the issue of relinquishment, which is Bill Joy's most controversial recommendation and personal commitment. Forgoing fields such as nanotechnology is untenable. Nanotechnology is simply the inevitable end result of a persistent trend toward miniaturization that pervades all of technology. It is far from a single centralized effort but is being pursued by a myriad of projects with many diverse goals.

Furthermore, abandonment of broad areas of technology will only push them underground, where development would continue unimpeded by ethics and regulation. In such a situation, it would be the less stable, less responsible practitioners (for example, the terrorists) who would have all the expertise.

The constructive response to these dangers is not a simple one: It combines professional ethical guidelines (which already exist in biotechnology and are currently being drafted by nanotechnologists), oversight by regulatory bodies and the development of technology-specific "immune" responses, as well as computer-assisted surveillance by law enforcement organizations. As we go forward, balancing our cherished rights of privacy with our need to be protected from the malicious use of powerful 21st-century technologies will be one of many profound challenges.

Technology will remain a double-edged sword, and the story of the 21st century has not yet been written. It represents vast power to be used for all humankind's purposes. We have no choice but to work hard to apply these quickening technologies to advance our human values, despite what often appears to be a lack of consensus on what those values should be. ◊

likely. My preferred way for doing this, which has served me well, though not flawlessly, for the last 30 years, is this: Put in a salad bowl the wildest, most forward-thinking technological ideas that you can imagine. (This is the craziness part.) Then add your best sense of what will be useful to people. (That's the rational part.) Start mixing the salad. If you are lucky, something will pop up that begins to qualify on both counts. Grab it and run with it, since the best way to forecast the future is to *build* it. This forecasting approach combines "nonlinear" ideas with the "linear" notion of human utility, and with a hopeful dab of serendipity.

Ray observes that technology is a double-edged sword. I agree, but I prefer to think of it as an axe that can be used to build a house or chop the head off an adversary, depending on intentions. The good news is that since the angels and the devils are inside us, rather than within the axe, the ratio of good to evil uses of a technology is the same as the ratio of good to evil people who use that technology…which stays pretty constant through the ages. Technological progress will not automatically cause us to be engulfed by evil, as some people fear.

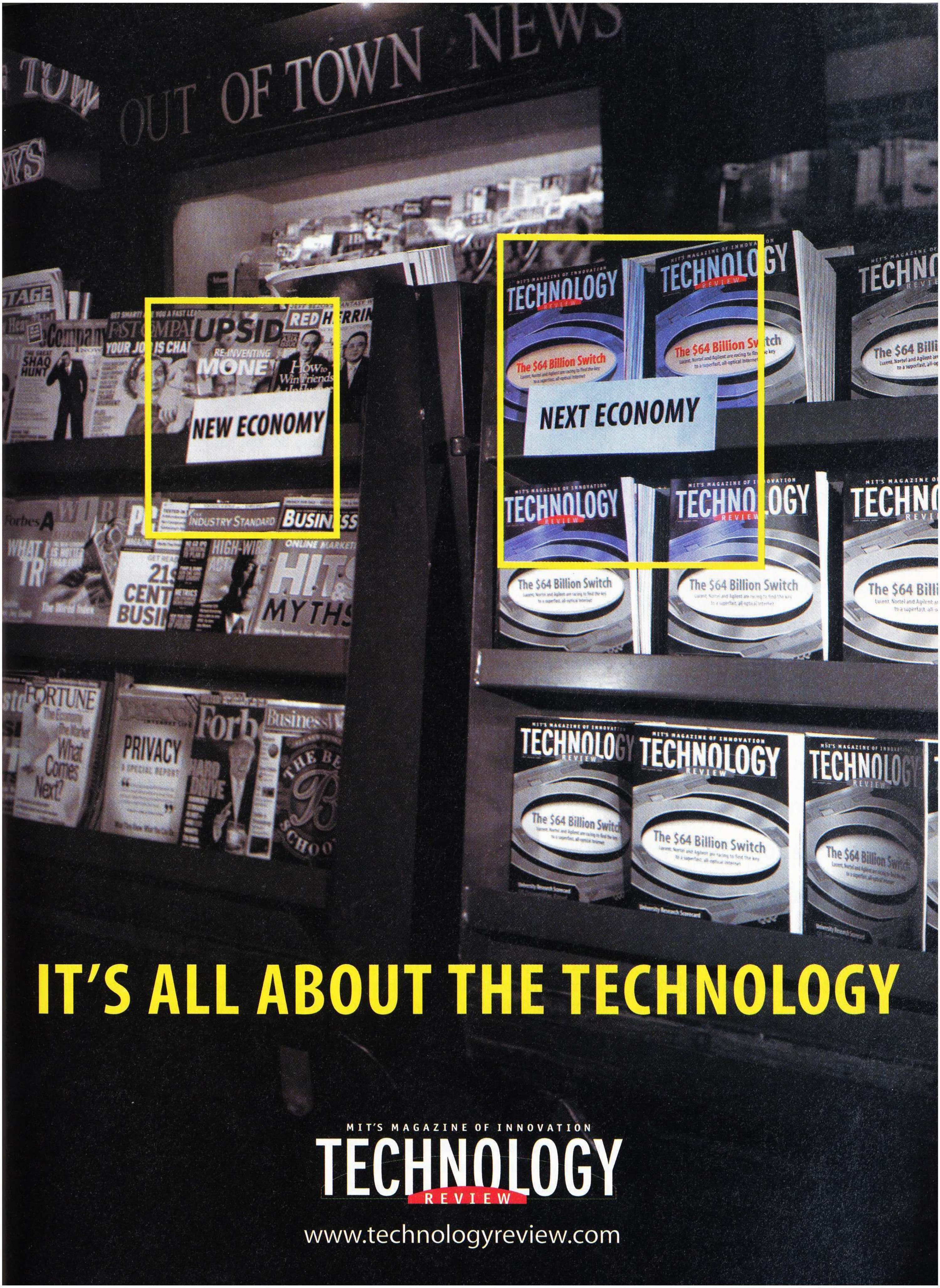
But for the same reason, potentially harmful uses of technology will always be near us, and we will need to deal with them. I agree with Ray's suggestions that we do so via ethical guidelines, regulatory overviews, immune response and computer-assisted surveillance. These, however, are partial remedies, rooted in reason, which has repeatedly let us down in assessing future technological directions. We need to go further.

As human beings, we have a rational, logical dimension, but also a physical, an emotional and a spiritual one. We are not fully human unless we exercise all of these capabilities in concert, as we have done throughout the millennia. To rely entirely on reason is to ascribe omniscience to a few ounces of meat, tucked inside the skull bones of antlike creatures roaming a small corner of an infinite universe—hardly a rational proposition! To live in this increasingly complex, awesome and marvelous world that surrounds us, which we barely understand, we need to marshal everything we've got that makes us human.

THE NOVELTY OF MODERN TOOLS IS COUNTERBALANCED BY THE CONSTANCY OF ANCIENT NEEDS. *–Dertouzos*

This brings us back to the point of my column, which is also the main theme of this discussion: When we marvel at the exponential growth of an emerging technology, we must keep in mind the constancy of the human beings who will use it. When we forecast a likely future direction, we need to balance the excitement of imaginative "nonlinear" ideas with their potential human utility. And when we are trying to cope with the potential harm of a new technology, we should use all our human capabilities to form our judgment.

To render technology useful, we must blend it with humanity. This process will serve us best if, alongside our most promising technologies, we bring our full humanity, augmenting our rational powers with our feelings, our actions and our faith. We cannot do this by reason alone! ◊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Where Have All the Computers Gone?

The following document arrived at the offices of *Technology Review* in a time capsule dated 2020. It purports to be a history of computers written by computer scientist-turned-historian John Seely Brown. In the late 20th century, Dr. Brown served as director of Xerox Corporation's Palo Alto Research Center.

ILLUSTRATION BY JAMES STEINBERG

The history of computers is actually quite simple. In the beginning there were no computers. Then there were computers. And then there were none again. Between the second and the third stage, they simply disappeared. They didn't go away completely. First they faded into the background. Then they actually merged with the background.

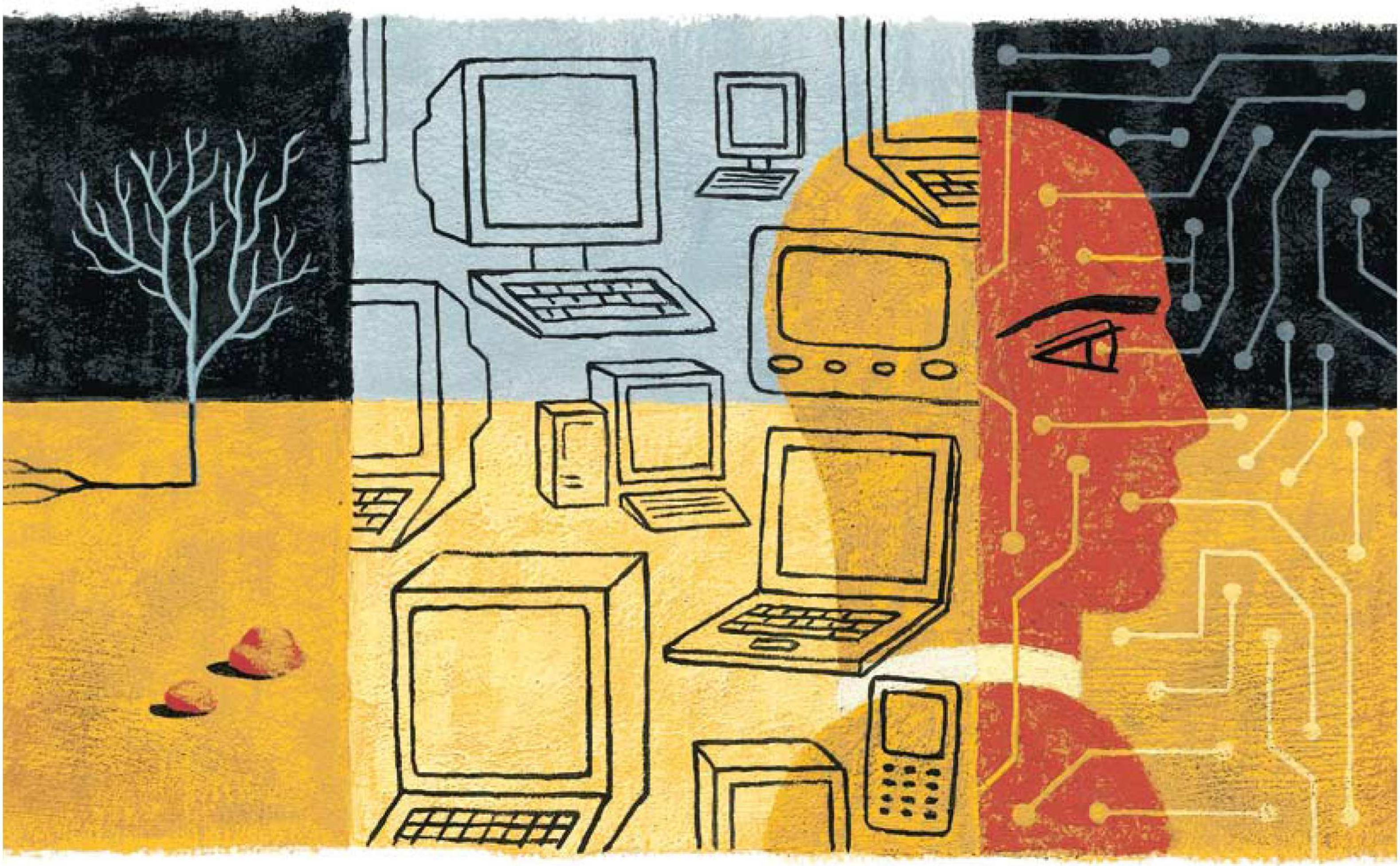
These different stages of computing came to be known in terms of their central motifs: The initial stage after they emerged from the back rooms into the public was the era of personal computing, which spanned the 1980s and early 1990s. With the advent of the Internet and the World Wide Web, this era seamlessly became the age of social computing, sometimes called ubiquitous computing, which began in the mid-1990s and lasted some two decades. This age was characterized by millions of computers, information appliances and storage devices that were interconnected—creating a vast information medium that supported all kinds of communities of interest. This new medium offered access to nearly any information residing anyplace in the world.

Roughly 15 years into the 21st century, the social computing stage morphed into the period called ecological or symbiotic computing. Structural matter (atoms) and computing (bits) became inseparable. Zillions of sensors, effectors and logical elements (made of organic and inorganic materials) were interconnected via wireless, peer-to-peer technologies, producing smart, malleable stuff used to build smart appliances, buildings, roads and more. It was during this era that computers disappeared. In their place, nearly every physical artifact harbored some computationally based brainpower that helped it know where it was, what was near it, when it was moved and so on. In a way, the inorganic world took on organic properties, using computing to transparently modulate responses to the environment.

But how did this come to be? During the personal computing stage, computers became increasingly powerful, but they also became harder to use. Moore's Law, stating that computing power would double every 18 months, seemed to hold for hardware. But robust software never could keep up. The result was that personal computers remained hard to use. The graphical user interfaces of the 1980s, at least, made systems somewhat manageable. But even that degree of usability faded in the second era of computing, when designers tried to extend this interface motif to navigating the vast information and document spaces of the Web. Those who surfed the Net all day long just ended up feeling disoriented or lost. More casual users felt overwhelmed with the volumes of irrelevant information given them by their intelligent agents, or "bots" (as these were often called at the turn of the 21st century).

Eventually the Web became a jungle of information pathways with no cues to help folks to their destinations, much like the center of a megacity without reliable signs or guides. Urban architects and social theorists were called on to help technologists see the resources that lay latent in the social and physical context. Humans, it was pointed out, used the context around objects and events to navigate the world and get things done. For example, they found out what was worth reading when a friend recommended a book or when they heard about an important article at work.

It turned out that interaction with other people was the key. Humans wanted technology to help them keep better connected to each other and to enhance their awareness of events around them. But they didn't want to have to *attend* to



every little thing; all they wanted was a virtual awareness that would take place subconsciously, much like how the visual system works in the physical world.

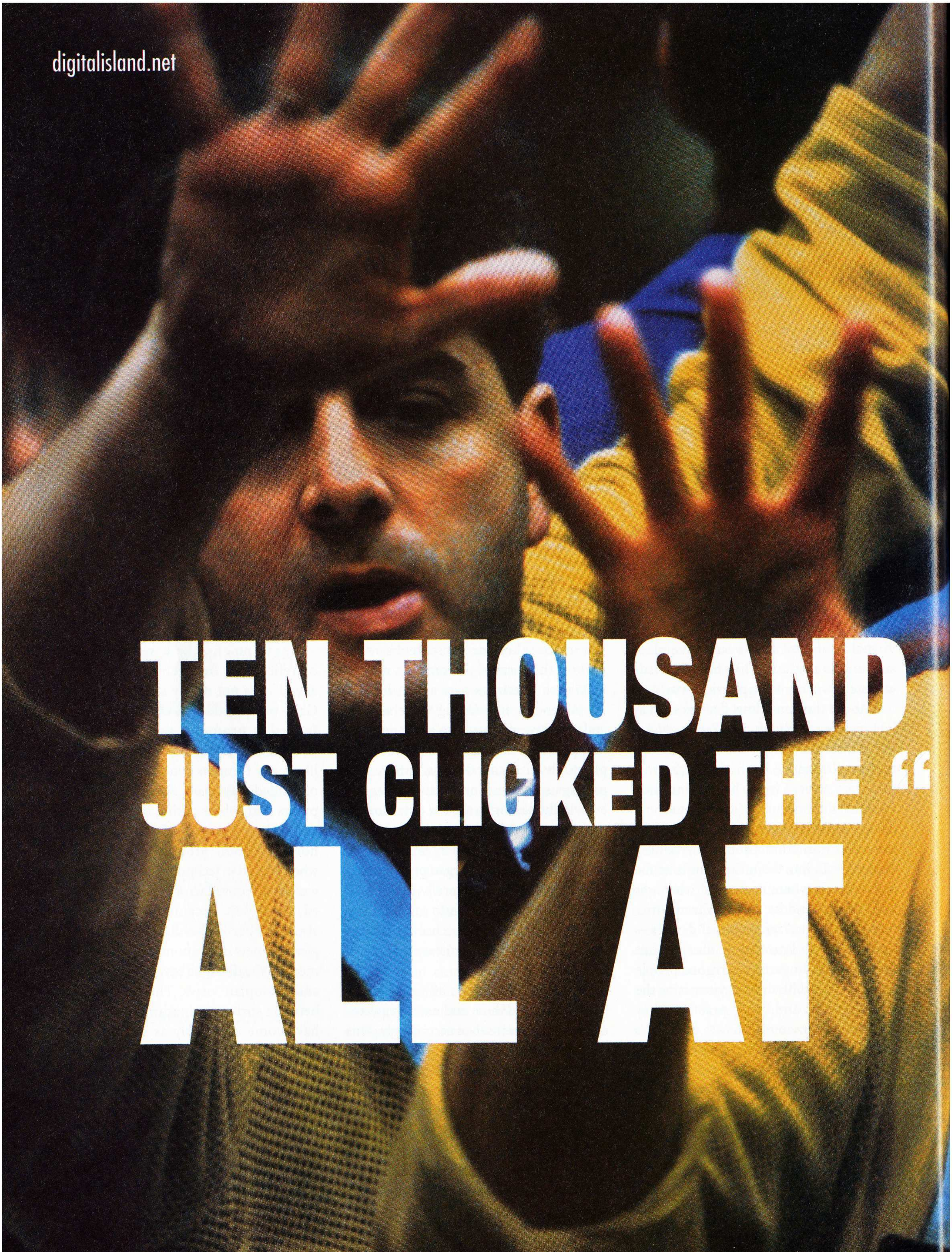
About the same time, devices such as laptops, pagers, phones and Personal Digital Assistants (PDAs) shrank so much that an alternative to the keyboard was necessary. Speech input helped, but then a major shift occurred. Computational devices started to have sensors, accelerometers and miniature Global Positioning Systems built into them. Such units let the device know where it was and what was happening. And as things shrank further—leading to "zero volume" devices—users came to know even more about their surroundings. Furthermore, people could interact with these devices using the same gestures and other practices they already used to communicate with each other. Even a person's key chain or PDA could interpret gestures of waving, tilting, squeezing and shaking as its owner interacted with it. For instance, users would tilt the device to scroll through a Web page, shake it to erase something and squeeze it to select an item, much like a mouse click. It all seemed so natural, taking on the properties of an animated conversation. The interface became transparent starting around the turn of the century, and by 2005 such interfaces were everywhere.

Although embedding these sensors and primitive effectors into appliances was first done to enable people to interact with physically shrinking devices, a more surprising use of these innovations emerged, eventually leading to the era of ecological computing. In this era, in addition to building sensors, accelerometers and effectors into devices, designers began putting them in the environment. Literally millions of these items were placed into road surfaces so that a highway could sense the flow of traffic and then communicate that information along its surface.

Thus today, cars are aware of traffic patterns around them and use that awareness to route themselves accordingly. This helps avoid congestion and with it pollution. In similar ways, sensors in office buildings, houses and factories respond in subtle but effective ways to minimize detrimental effects and harmonize human activity with the environment. Indeed, through computing, our environment has been made aware of itself, giving rise to the era of ecological or symbiotic computing.

As we now look back we breathe a sigh of relief—for the technological "road ahead" was not nearly as straight as Bill Gates portrayed in his classic 1995 book. Indeed, a profound wake-up call was issued a short while later by Bill Joy, who, like many futurists before him, painted a one-sided dystopian view of nanocomputers and robots taking over the world and enslaving mankind. It's true that technology remains problematic. But those who believed in technological determinism were again proved wrong. Society responded, the public became better educated about the perils of radical new technologies, and new institutions emerged to help mediate the dialogue between the utopian and dystopian views. This co-evolution between society and technology may not have come as quickly as some wished. Nonetheless, it occurred in a way that forced the technological world to become less arrogant and more humble. ◊

John Seely Brown is chief scientist of Xerox and chief innovation officer at 12 Entrepreneuring. He is co-author of The Social Life of Information *(Harvard Business School Press, 2000).*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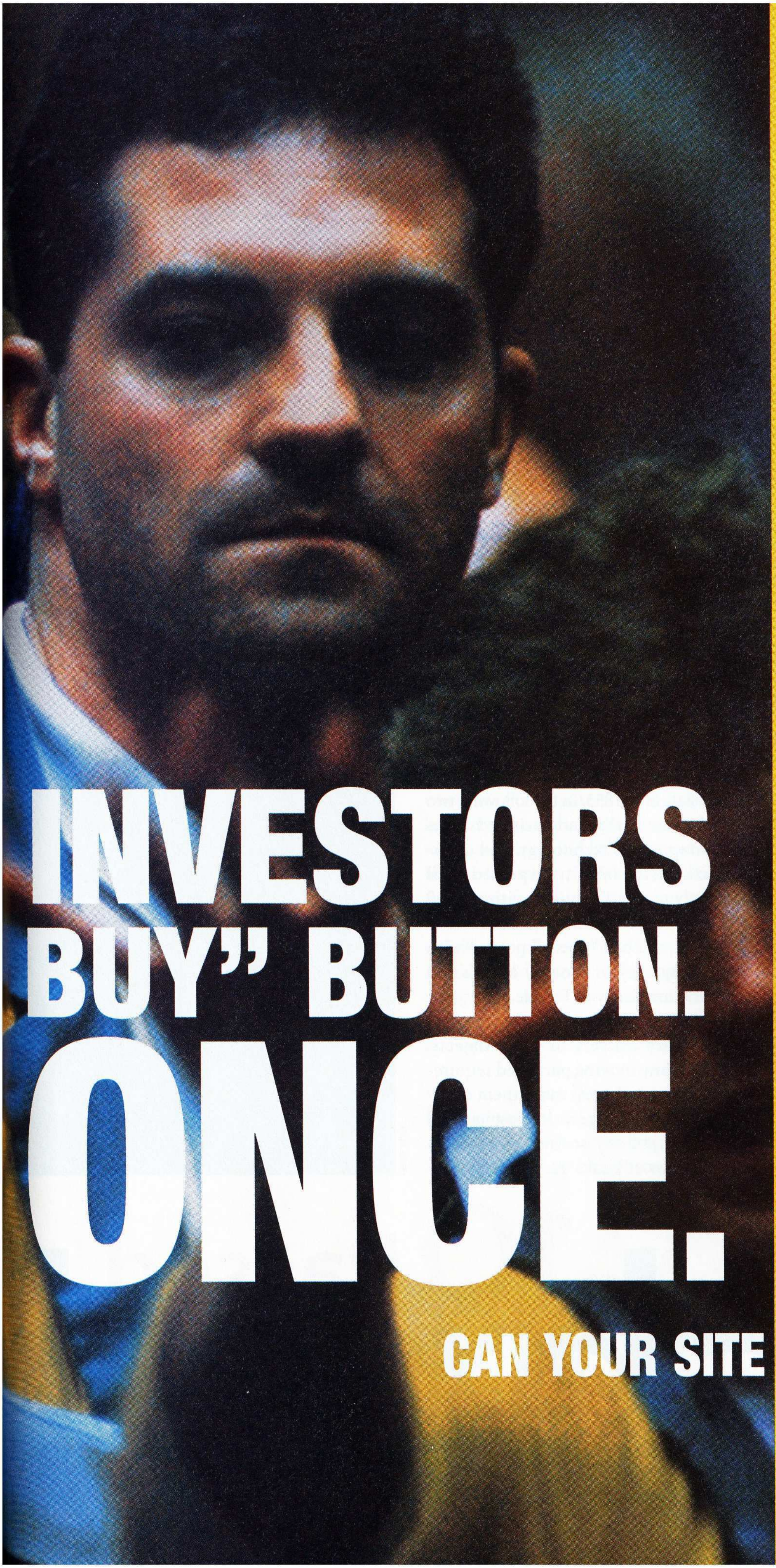

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HANDLE IT?

10 Passed Technologies

BY NICK MONTFORT

Not every disappearing technology deserves that fate. Sometimes the "losers" have an elegance and simplicity the "winners" lack. Here are 10 examples.

Electric Trolley

Streetcars, the country's first major form of public transportation, were challenged by a cheaper form of transit that gained ground through the 1930s—the bus. A persistent theory that General Motors orchestrated the demise of America's streetcar lines is disputed by transit historians, but even without corporate conspiracies, bus systems had the clear advantage of running on existing roads—and they paid no market penalty for the greater noise and pollution they generated.

After World War II, a few major cities seized on a way to get the best of both worlds: Keep the streetcar's electrical

CORBIS IMAGES

cables suspended over the streets, hook electric buses up to them and remove the tracks, making the streets safer for cars. Electric buses, developed earlier in the century, only caught on when streetcars made way for them. About 1,000 trolley buses are still running on electrical grids in North American cities today, mostly in San Francisco and Vancouver, B.C. Since a new fleet (with custom cars and new infrastructure) would be a substantial investment for any city, and with natural-gas and battery-powered electric vehicles on the rise, it's unlikely the electric-bus grid will grow.

Pneumatic Post

Telegraph lines, the 19th-century analog of today's fiber-optic cable, had their own "last mile" problem—getting the message to the recipient. One 19th-century solution: a pneumatic messaging system, host to hurtling, paper-stuffed capsules sucked or pushed along by air pressure. A system like this first linked the London Stock Exchange to the city's main telegraph station in 1853. In the following two decades, the Berlin and Paris exchanges also adopted the technology, and pneumatic systems later transported mail through major European cities—and through New York, until 1953. (The Paris messages, dubbed "pneus," pop up with some frequency in Proust.) Mail is still sent pneumatically in Prague.

Air-driven communication systems offer breezy delivery of small objects, but the many moving parts and requirements for airtightness make them costly to maintain on a large scale. Hospitals and large stores still rely on them, as do drive-up windows at banks. As ATM use continues to grow, the giant pneumatic sucking sound will grow quieter still.

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Amiga

AMIGA

In 1984, Apple's Macintosh brought the graphical user interface (GUI) to consumers. The next year, multimedia computing arrived in the form of Commodore's Amiga 1000. The Amiga had the first personal computer operating system to offer pre-emptive multitasking, allowing running programs to utilize the processor as efficiently as possible. (Pre-emptive multitasking will arrive this year on the Macintosh with the release of OS X.) In addition, the Amiga, which could emulate the Macintosh and later the IBM PC, cost half as much as other computers of the day.

The Amiga's graphics and sound were so extreme that many people could understand it only as a sort of ultrapowerful video game system. It was the first computer to display more than 16 colors, could be used to edit video and featured four-channel digital stereo sound at a time when other computers could only emit beeps. But business users found the software base of the IBM PC a stronger selling point. Meanwhile, the Atari ST challenged the Amiga for the slim early multimedia market, and Commodore began to unravel. Still, Amiga has survived Commodore's demise—and ownership by several other companies. A new version of the Amiga operating system was released in 1999, and new hardware is in development.

Ribbon Microphone

The classic "ribbon" microphone that became an icon of radio broadcasting—RCA's model 44A— was a hefty 8-pound device introduced in 1931.

Unlike conventional microphones, in which air pressure from sound waves moves a diaphragm to produce an electrical signal, in a ribbon microphone, a tiny piece of foil hovering between two magnets created a signal when it moved in response to air velocity. Ribbon microphones' warm sound worked particularly well with a singer's or broadcaster's voice, and they were uniquely useful in radio drama, as Bose fellow William R. Short of Bose Corp. in Framingham, Mass., explains. "They have this figure-eight pattern—they accept sound from the front and back, while rejecting sound from the sides." As a result, actors at different positions around the microphone could sound as if they were far apart, even in different rooms.

The 44A was too bulky for widespread use in television and wasn't effective outside the studio because wind gusts could blow the foil from between the magnets. Yet ribbon microphones remain popular today "because their unique transparent sound quality was better than carbon and early condenser microphones," says audio engineer Bob Speiden, whose own ribbon microphones, developed in the 1980s, are still manufactured by Royer Labs.

ARCHIVE PHOTOS

WordStar

Long before Microsoft Word's talking paper clip started bending users out of shape, there was a feature-rich but trusty word processor: WordStar. According to telecommunications columnist John Dvorak, Rob Barnaby programmed the first version, released in 1979, in assembly language in four months, a feat that some at IBM later estimated was equal to 42 years of effort by a normal programmer.

EYEWIRE

WordStar was the first word processor to compute page breaks on the fly. It introduced a new way of moving up, left, right or down in a document, by pressing CONTROL-E, S, D or X. Variants of this "WordStar diamond" (named for the arrangement of those keys) are still used in some programmers' text editors today. WordStar also offered handy letter-transposing key commands and a view of the document that looked much like the final printout.

By 1984, WordStar International was the country's largest software company, but WordStar2000, released in 1985, fared poorly against rival WordPerfect, and the company fell from its lead position. Still, WordStar laid the groundwork for today's WYSIWYG, or "what you see is what you get," systems. Perhaps its simplicity relative to today's word processors is a virtue rather than a defect: A present-day WordStar Users Group testifies that the influential early application is still in use.

Edison's Wax Cylinder

Audiophiles lament the passing of vinyl, which they perceive as having a richer sound than the compact disc. But the recorded disc (first made of vulcanite, then shellac and finally vinyl) was in its own day an upstart technology, elbowing out a superior medium for recording sound: the soda-can-shaped wax cylinder first manufactured by Thomas Edison in 1877. Edison chose to produce wax cylinders instead of discs because they were technically superior. In his book *The Invisible Computer*, technology-design guru Donald A. Norman explains that, with the cylinder, "each part passes under the stylus at the same speed. With discs, the outside edge moves past the stylus more rapidly than the parts near the center, and so the sound at the center deteriorates." Another plus: People could make their own recordings on wax cylinders, while records were read-only.

Despite their technological virtues, Edison's wax cylinders failed in the marketplace early in the century. RCA, which championed discs, rounded up a more recognizable group of recording artists. Records were also easier to stamp out en masse. Norman points to Edison's cylinders as the principal example of a superior technology defeated by one that was inferior but "good enough." Although the last cylinders were manufactured in 1929, the year Edison's company closed, the band They Might Be Giants went to the Edison National Historic Site in New Jersey to record "I Can Hear You," a track of their 1996 album *Factory Showroom,* on wax cylinder.

Slide Rule

"No engineering student would dare venture out in public…without his (or her) slide rule in its 'holster' and hanging from the belt," recalls Professor Emeritus Wayne McMorran of California Polytechnic State University in his online history of that school's electrical engineering department. "If you were really into it, you bought a really long one (about 20 inches) so you could get better precision."

Slide rules were developed in England to allow multiplication by use of logarithms—a mathematical idea set out by Scottish mathematician John Napier in 1614. They ruled supreme for more than three centuries, widely used by engineers and navigators. Because the product of any two numbers is equal to 10 raised to the power of the sum of their logarithms, any multiplication problem can be more simply restated as an addition problem. With the rise of the mechanical slide rule, one could make these computations by positioning two ruled straightedges (or in some cases, circles), without having to look up numbers in a logarithm table.

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In the early 1970s, cheap handheld electronic calculators vanquished slide rules. Although they are no longer manufactured, slide rules are still used in education: A slide-rule lending program run by Wichita, Kan., high school teacher Bill Cooper teaches important mathematical concepts that are crucial when using a slide rule, such as orders of magnitude and significant digits.

PHOTODISC

HULTON GETTY

Reel Mower

Although lawn mowers call to mind the green grass oceans that surround modern suburban homes, the first one was patented in England in 1830 by Edwin Budding. Budding's mower wasn't driven by an internal combustion engine, of course; it was pushed along quietly, if effortfully, by the human operator. The cylindrical reel mower was displaced in the United States by the motorized rotary mower, part of the post-World War II crop of home-automation devices.

While the gasoline-powered mower is easier to push and cuts closer, it's annoyingly noisy and generates bags of grass cuttings that are better left to mulch back into the lawn. It also belches pollution: The U.S. Environmental Protection Agency estimates that up to 5 percent of domestic air pollution comes from garden equipment powered by extremely inefficient two-stroke engines that burn both oil and gasoline. Another woe of the prevailing technology: A U.S. Consumer Product Safety Commission study reported 385,000 injuries from power mowers over a recent seven-year period, while reel mowers, although much less frequently used, caused no reported injuries at all during that time. Now re-engineered using more lightweight materials, reel mowers are making a quiet comeback; according to Michigan's Department of Environmental Quality, sales of reel mowers in the past 15 years have more than doubled.

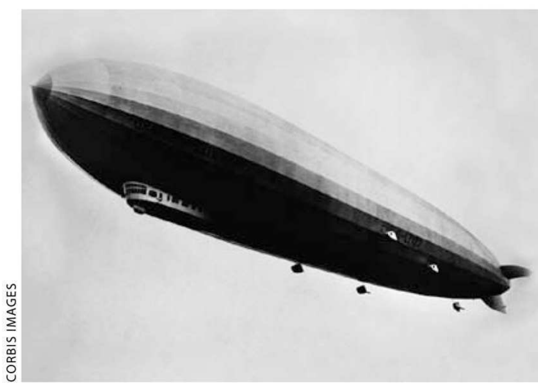
Automatic Watch

In 1780, Parisian watchmaker Abraham-Louis Breguet devised a timepiece that did not need to be wound; the everyday jostling of carrying the watch drove a pendulum that kept the watch running. This automatic watch was, in the words of modern-day poet David Slavitt, "a frugal wheel hoarding all human movement / for its own to spend at a jeweled leisure." Early automatic watches, nestled in their owners' watch pockets, didn't get bounced around enough to work well. Only in the 1920s, when watches migrated to the more mobile wrist, did the automatic watch (also called "perpetual" or "self-winding") become truly successful. One Swiss watchmaker, Rolex, became particularly well known by billing its watches as waterproof: Since the stem no longer needed to be used for winding, automatic watches were more resistant to water. The automatic watch did have to be worn daily in order to stay wound, but it was much less likely to wind down accidentally than earlier mechanical watches. It also kept time better, because the watch spring stayed at a rather consistent tension rather than winding down a great deal and then suddenly back up all the way.

Today, most people wear quartz battery-powered watches, which are accurate and can be made cheaply, but automatic watches are still successful in niche markets, including Rolex's high-end market. Those mechanical watches that are still made today are largely automatic.

Airship

On May 6, 1937, as a stunned crowd looked on, Ferdinand Graf von Zeppelin's majestic airship, the Hindenburg, exploded—a violent end for 36 human lives and also, since public faith in airships was destroyed, for a promising transportation technology. An earlier hard-shelled airship, the famous Graf Zeppelin (named for its inventor), could attain speeds of 130 kilometers per hour and in 1929 circumnavigated the globe in a record time of less than 22 days. Many dangers were associated with this transportation advance, though—the Hindenburg was only the most spectacular of numerous disasters.



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While soft-sided blimps serve as flying billboards and camera platforms for sporting events, a German company, CargoLifter AG, plans to build an airship, the CL160, that could bear 160-ton loads across the ocean, which only boats might otherwise manage—buoyed by nonflammable helium, not the hydrogen that filled the Hindenburg. Plans call for a fleet of 50. ◊

WANT TO CHANGE THE STRATEGIC LAND
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SEAT PAGINE GIALLE SpA Pending €60,000,000,000 Has agreed to merge with **tin.it**	NORTEL NETWORKS May 2000 $50,200,000,000 Spin-off of 36.9% interest held by **BCE**	Pacific Century CyberWorks August 2000 $36,500,000,000 Acquired **Cable & Wireless Hong Kong Telecom**
ASCEND June 1999 $24,000,000,000 Merged with **Lucent Technologies**	VeriSign The Sign of Trust on the Net June 2000 $21,000,000,000 Acquired **Network Solutions**	VERITAS Pending $20,000,000,000 Agreement to acquire 32% interest and assets of **Seagate Technology**
LYCOS October 2000 $12,500,000,000 Acquired by **Terra Networks**	france telecom WIND Pending €12,100,000,000 Agreement to merge with **Infostrada**	aspect DEVELOPMENT June 2000 $9,300,000,000 Merged with **i2 Technologies**
wh whittman-hart March 2000 $7,900,000,000 Merged with **USWeb/CKS**	NORTEL NETWORKS October 2000 $7,800,000,000 Acquired **Alteon WebSystems**	Cerent the Revolutionary network element. November 1999 $7,500,000,000 Acquired by **Cisco Systems**
ALCATEL May 2000 $7,100,000,000 Acquired **Newbridge Networks**	phone.com Pending $7,000,000,000 Agreement to merge with **Software.com**	Chromatis June 2000 $5,000,000,000 Acquired by **Lucent Technologies**

EMERGING TECHNOLOGIES
10
THAT WILL CHANGE THE WORLD

THE TECHNOLOGY REVIEW TEN

What if you had a crystal ball that foretold the future of technology? Imagine, for example, if you had known in 1990 just how big the Internet was going to be 10 years hence. Sorry, that crystal ball doesn't exist. But in this special issue of *Technology Review*, we offer you the next best thing: the educated predictions of our editors (made in consultation with some of technology's top experts). We have chosen 10 emerging areas of technology that will soon have a profound impact on the economy and on how we live and work. These advances span information technology, biotechnology and nanotechnology—the core of *TR* coverage in every issue. All of these areas merit special attention in the decade to come. In each area we've chosen to highlight one innovator who exemplifies the potential and promise of the field. Keep this issue around and see how well our predictions hold up—even without the aid of that crystal ball. —*The Editors*

Duke University's Miguel Nicolelis handles a robotic arm. Brain signals from an owl monkey (seen on the monitors to the right) control the arm's movement.

MIGUEL NICOLELIS

Brain-Machine Interfaces

Belle, a nocturnal owl monkey small enough to fit comfortably in a coat pocket, blinks her outsized eyes as a technician plugs four connectors into sockets installed in the top of her skull. In the next room, measurements of the electrical signals from some 90 neurons in Belle's brain pulse across a computer screen. Recorded from four separate areas of Belle's cerebral cortex, the signals provide a window into what her brain is doing as she reaches to touch one of four assigned buttons to earn her reward—a few drops of apple juice. Miguel Nicolelis, a Duke University neurobiologist who is pioneering the use of neural implants to study the brain, points proudly to the captured data on the computer monitor and says: "This readout is one of a kind in the world."

The same might be said of Nicolelis, who is a leader in a competitive and highly significant field. Only about a half-dozen teams around the world are pursuing the same goals: gaining a better understanding of how the mind works and then using that knowledge to build implant systems that would make brain control of computers and other machines possible. Nicolelis terms such systems "hybrid brain-machine interfaces" or HBMIs. Recently, working with the Laboratory for Human and Machine Haptics at MIT, he scored an important first on the HBMI front, sending signals from individual neurons in Belle's brain to a robot, which used the data to mimic the monkey's arm movements in real time.

In the long run, Nicolelis predicts that HBMIs will allow human brains to control artificial devices designed to restore lost sensory and motor functions. Paralysis sufferers, for example, might gain control over a motorized wheelchair or a prosthetic arm—perhaps even regain control over their own limbs. "Imagine," says Nicolelis, "if someone could do for the brain what the pacemaker did for the heart." And, in much the same way that a musician grows to feel that her instrument is a part of her own body, Nicolelis believes the brain will prove capable of readily assimilating human-made devices.

Ongoing experiments in other labs are showing that this idea is credible. At Emory University, neurologist Phillip Kennedy has helped severely paralyzed people communicate via a brain implant that allows them to move a cursor on a computer screen *(see "Mind Over Muscles," TR March/April 2000)*. And implants may also shed light on some of the brain's unresolved mysteries. Nicolelis and other neuroscientists still know relatively little about how the electrical and chemical signals emitted by the brain's millions of neurons let us perceive color and smell, or give rise to the precise movements of Brazilian soccer players—whose photos adorn the walls of the São Paolo native's office. "We don't have a finished model of how the brain works," says Nicolelis. "All we have are first impressions."

Others in Brain-Machine Interfaces

Organization	Project
Andy Schwartz (Arizona State University)	Neural control of robotic arm
John Donoghue (Brown University)	Brain representation of movement
Richard Andersen (Caltech)	Improved neuroelectrode systems
Phillip Kennedy, Roy Bakay (Emory University)	Communication systems for paralyzed patients

Nicolelis' latest experiments, however, show that by tapping into multiple neurons in different parts of the brain, it is possible to glean enough information to get a general idea of what the brain is up to. In Belle's case, it's enough information to detect the monkey's intention of making a specific movement a few tenths of a second before it actually happens. And it was Nicolelis' team's success at reliably measuring tens of neurons simultaneously over many months—previously a key technological barrier—that enabled the remarkable demonstration with the robot arm.

Still, numerous stumbling blocks remain to be overcome before human brains can interface reliably and comfortably with artificial devices, making mind-controlled prosthetic limbs or computers more than just lab curiosities. Among the key challenges is developing electrode devices and surgical methods that will allow safe, long-term recording of neuronal activities. Nicolelis says he's begun working with Duke's biomedical engineering department to develop a telemetry

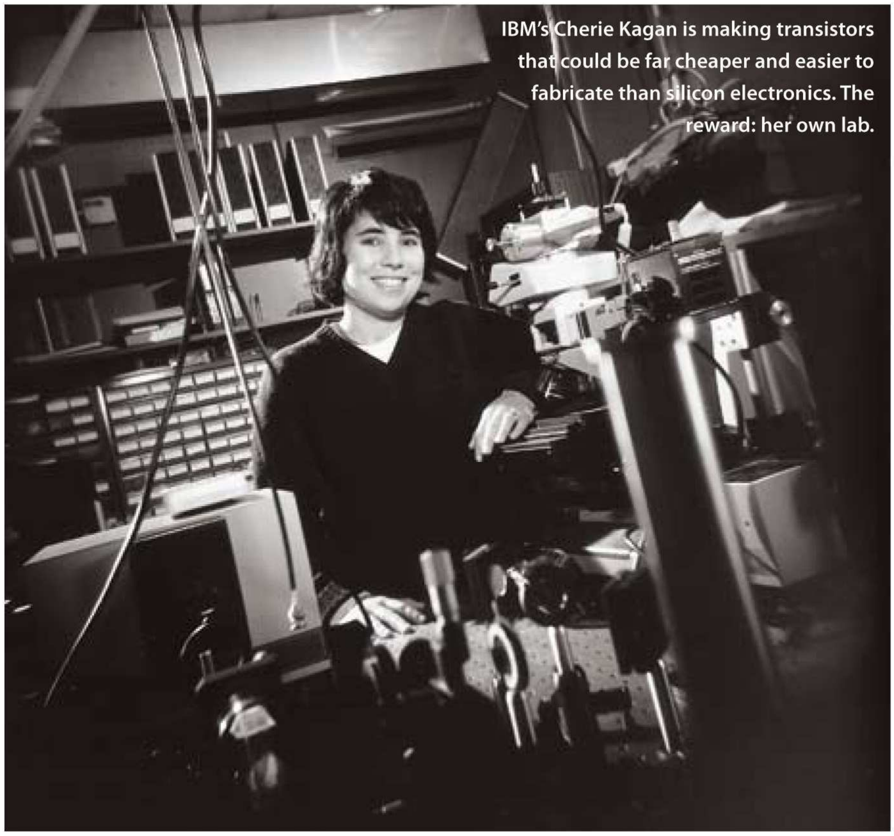
Photograph by PATRICIA MCDONOUGH

chip that would collect and transmit data through the skull, without unwieldy sockets and cables. And this year Nicolelis will become co-director of Duke's new Center of Neuroengineering and Neurocomputation, which will explore new combinations of computer science, chip design and neuroscience. Nicolelis sees the effort as part of an impending revolution that could eventually make HBMIs as commonplace as Palm Pilots and spawn a whole new industry—centered around the brain.

—Antonio Regalado

CHERIE KAGAN

Flexible Transistors



IBM's Cherie Kagan is making transistors that could be far cheaper and easier to fabricate than silicon electronics. The reward: her own lab.

The implementation of pervasive computing—the spread of digital information throughout society—will require electronics capable of bringing information technology off the desktop and out into the world *(see "Computing Goes Everywhere," p. 52)*. To digitize newspapers, product labels and clothing, integrated circuits must be cheap and flexible—a tough combination for today's silicon technology. Even the cheapest form of silicon electronics—the cut-rate "amorphous" silicon used to drive laptop display screens—is too pricey. What's more, it's difficult to incorporate silicon electronics on bendable surfaces such as plastics.

Technology innovators are taking a couple of routes around these limits. Some researchers are trying to reinvent amorphous silicon. Others have abandoned inorganic compounds like silicon to develop transistors based on organic (carbon-based) molecules or polymers. These organic electronics are inexpensive to manufacture and compatible with plastic substrates. Indeed, research teams at places such as Lucent Technologies' Bell Labs, England's University of Cambridge and Pennsylvania State University have made impressive progress, and commercial products are nearing the market. Last fall, for example, Philips Research in Eindhoven, the Netherlands, showed off the first prototype of a rudimentary display driven by polymer semiconductors. But there's a catch: Organics are far slower than their silicon cousins.

Others in Flexible Transistors

Organization	Project
Lucent/Bell Labs (Murray Hill, NJ)	Organic circuits
Richard Friend (University of Cambridge)	Organic light-emitting diodes
Joseph Jacobson (MIT)	Printed inorganics
Thomas Jackson (Penn State)	Organic transistors

Now, a 31-year-old materials scientist at IBM, Cherie Kagan, may have opened the door to cheap, flexible electronics that pack the mojo needed to bring ubiquitous computing closer. Her breakthrough? A compromise: transistors made from materials that combine the charge-shuttling power and speed of inorganics with the affordability and flexibility of organics.

These hybrids were created by chemist David Mitzi at IBM's Thomas J. Watson Research Center in Yorktown Heights, N.Y. By the time Kagan arrived at Watson in 1998 following a stint at Bell Labs (she earned a PhD from MIT in 1996), Mitzi had already shown that his materials possessed intriguing electronic properties. Kagan had a hunch they might make good transistors. But she needed quick results; she'd been hired as a postdoc—a limited-time offer.

At the outset, the transistors flipped on and off sluggishly. "The first times, I didn't want to calculate [the speed]," says Kagan. But she kept tweaking, and in less than a year she had increased the mobility of electric charges through her transistors by four orders of magnitude—matching the speed of amorphous silicon and far exceeding most organic transistors. The results won her a staff position and her own lab at IBM.

Kagan has since increased the speed by another 50 percent; further fine-tuning, she believes, could provide at least another doubling in acceleration. Not only may the hybrids be far faster than amorphous silicon, they have a key advantage over silicon-based electronics. Like some organic materials used to make transistors, the hybrid materials can be dissolved and printed onto paper or plastic just like particles of ink. "I make my materials in a different lab and carry them over and add some liquid and spin them on," says Kagan. "It's not very sophisticated, which is sort of the goal, right? You really want it to be cheap."

Thomas Jackson, a transistor expert at Penn State who is developing organic circuits, says Kagan's "fledgling results" could pave the way for fast yet flexible electronics. Jackson credits Kagan with seizing the opportunity. "Not only does she have her own pocket of competence,

Photograph by LARRY BUSACCA

but she's able to look around and see exciting possibilities and then bring things together. IBM has been working on these sorts of materials for some time, but it took the energy and enthusiasm and vision and perspective of Cherie to translate that into a thin-film transistor."

The transistors could compete with organic electronics in a variety of applications, such as radio-frequency product ID tags. And then there's the $20 billion-per-year market for flat-panel video displays, where the speed of Kagan's transistors could really make a difference. Quicker circuits would deliver sharper displays than those driven by amorphous silicon at a fraction of the cost. That would open the door to affordable wall-sized displays or high-quality displays that pop out of your pen. If all goes well, the materials could be used in cheap, flexible displays within five years.

Of course, bright displays that fit in your pocket will require portable power, and that has Kagan pondering her next research challenge: cheap, flexible materials for solar cells to liberate pervasive computing from bulky batteries. "You aren't going to want to carry a battery around with your lightweight flexible display," she says. *—Peter Fairley*

USAMA FAYYAD

Data Mining

"Hello again, Sidney P. Manyclicks. We have recommendations for you. Customers who bought this title also bought..."

Intrusive? A touch of personal attention in the sterile world of e-shopping? Both, perhaps—but definitely a tour de force of database technology. Conventional databases sort though a few megabytes of structured data to find answers to specific queries. But compiling a simple recommendation list requires a system that can burrow through gigabytes of Web site visitor logs in search of patterns no one can anticipate in advance.

Welcome to data mining, also known as knowledge discovery in databases (KDD): the rapidly emerging technology that lies behind the personalized Web and much else besides. The emphasis here is on "emerging," says Usama Fayyad, who should know: data mining didn't exist as a field until he helped pioneer it.

In 1987, the Tunisian-born computer scientist was a graduate student at the University of Michigan. He had taken a summer job with General Motors, which was compiling a huge database on car repairs. The idea, he says, was to enable any GM service technician to ask the database a question based on the model of car, the engine capacity, and so on, and get a quick, appropriate response. Sounds straightforward. But, recalls Fayyad, "there were hundreds of millions of records—no human being could go through it all." The pattern recognition algorithm he devised to solve that problem became his 1991 doctoral dissertation, which is still among the most cited publications in the data-mining field.

Data mining proved to have surprisingly broad application. Fayyad left Michigan for NASA's Jet Propulsion Laboratory, where he applied his techniques to astronomical research. In particular, his algo-

Others in Data Mining

Organization	Project
Howard Wactlar (Carnegie Mellon)	Search very large video collections
Marti Hearst (University of California, Berkeley)	Automated discovery of new information from large text collections
Nokia Research Center (Helsinki, Finland)	Finding recurrent episodes in event sequence data
Raghu Ramakrishnan (University of Wisconsin)	Visual exploration of data on the Web

DigiMine's Usama Fayyad devises algorithms that detect meaningful patterns in massive collections of information.

Photograph by KAREN MOSKOWITZ

rithm helped in automatically determining which of some two billion observed celestial objects were stars and which were galaxies. The tool also helped find volcanoes on Venus from the huge number of radar images being transmitted from space probes. A geologist could retrieve the image of a previously identified volcano; the computer would then examine the picture for patterns and search through other images for similar patterns. That worked so well, Fayyad says, that "pretty soon the military intelligence people were all over us, wanting to use it. And so were doctors, who wanted to do automatic searches of radiology images." In 1995, in response to this widening interest, Fayyad and his colleagues planned a full-scale international conference on KDD. The conference drew about 500 participants, more than double what had been expected. (KDD 2000 drew 950.)

By this time, with the Internet gushing information onto everyone's desktop, the urgency for data mining was becoming evident in the corporate world. IBM and other industry giants sensed a market—and wanted in. Microsoft set its sights on Fayyad and enticed him to join the company's research labs. "They suggested that I take a look at databases in the corporate world," says Fayyad. "It was pretty sad. In many companies, the 'data warehouses' were actually 'data tombs': the data went in and were never looked at again." Fayyad joined Microsoft in 1996 and organized a new research group in data mining. "We looked at new algorithms for scaling up to very large databases—gigabytes or larger," he says.

By decade's end, Fayyad had caught the entrepreneurial bug sweeping through computer science labs. "I realized that even the organizations that loved the idea of data mining were having trouble just maintaining their data." What they needed, he reasoned, was a company to host their databases for them, and provide data-mining services on top of that. The result was digiMine, a Kirkland, Wash., startup that opened for business in March 2000 with Fayyad as CEO.

And the future of data-mining technology? Wide open, says Fayyad—especially as researchers begin to move beyond the field's original focus on highly structured, relational databases. One very hot area is "text data mining": extracting unexpected relationships from huge collections of free-form text documents. The results are still preliminary, as various labs experiment with natural-language processing, statistical word counts and other techniques. But the University of California at Berkeley's LINDI system, to take one example, has already been used to help geneticists search the biomedical literature and produce plausible hypotheses for the function of newly discovered genes.

Another hot area, says Fayyad, is "video mining": using a combination of speech recognition, image understanding and natural-language processing techniques to open up the world's vast video archives to efficient computer searching. For instance, when Carnegie Mellon University's Informedia II system is given an archive of, say, CNN news clips, it produces a computer-searchable index by automatically dividing each clip into individual scenes accompanied by transcripts and headlines.

Fayyad hopes that ultimately the techniques of data mining will become so successful and so thoroughly integrated into standard database systems that they will no longer be thought of as exotic. "People will just assume that their database software will do what they need."

—M. Mitchell Waldrop

RANJIT SINGH

Digital Rights Management

Sitting in his office in McLean, Va., Ranjit Singh is at ground zero of what may be the biggest—and bloodiest—of the many battles that will shape the Internet during the 21st century's initial decade. The battle lines are sharply drawn. On one side are owners of intellectual property, or content: books, music, video, photographic images and more. On the other are Internet users—think Napster—who want content to be freely distributed.

And then there is Singh, president of ContentGuard, a company that spun out of research at Xerox's Palo Alto Research Center (PARC) on a mission to commercialize content protection in a wired world. "The Internet changes everything," says Singh, 48, an England-born technology manager whose resume glitters with senior positions at Xerox, Citibank and Digital Equipment plus a number of startups. "The Internet," Singh continues, "allows perfect reproduction of digital content and totally frictionless distribution." A few mouse clicks send a work to millions of users, but the creators and owners of the content won't necessarily collect dime one *(see "Your Work Is Mine!"* TR *November/December 2000)*.

ContentGuard's Ranjit Singh manages access to online digital property.

Ouch! You can bet the pain felt by content owners who see their stuff flying everywhere via the Net will translate into action. Which is what Singh and ContentGuard are about. Digital rights management, or DRM, is "the catalyst for a revolution in e-content," says Singh. "DRM will allow content owners to get much wider and deeper distribution than

Photograph by CHRIS HARTLOVE

ever before," he maintains. "You can see who is passing your content to whom."

Stripped to its essence, DRM—as provided by ContentGuard and a number of competitors—amounts to an encryption scheme with a built-in e-business cash register. Content is encoded, and to get the key a user needs to do something—maybe paying money, maybe providing an e-mail address. DRM providers deliver the protection tools; it is up to content owners to set the conditions. ContentGuard uses a "multiple key" approach to content protection; anyone who received bootleg content would have to crack into it all over again. Thus, Singh explains, "even if a hacker cracks into a piece of content, he cannot distribute it."

So why isn't DRM ubiquitous? Two reasons. First, content owners are in the midst of a hard rethink about both pricing and distribution. Suddenly they are wrestling with issues of how to price three listens to a song, say, or a download of a low-resolution image that cannot be forwarded to others. "Content owners now are trying out different economic models for valuing content," says Singh, whose company provides DRM tools to, among others, John Wiley & Sons and Houghton Mifflin. "DRM opens many possibilities," he adds.

The second issue may be the more nettlesome: "The user experience has to hide the complexity of the protection technologies," says Singh. Users need to be able to buy the content they want "without needing special viewers or downloads and without putting the user through hoops," he argues. To resolve that, ContentGuard has forged multiple partnerships with digital standard-bearers such as Microsoft and Adobe Systems, and has extended its technology so that it applies across many media, including books, music and video.

Captivating as the possibilities of DRM are, it is still in its early days. Says John Schwarz, CEO of Reciprocal, Inc., a distributor of ContentGuard and other DRM solutions: "We are probably a year or so away from seeing broad adoption of DRM by the marketplace."

Some analysts are more skeptical: "I'm not convinced content can be protected in the Internet era," says Eric Scheirer, who tracks DRM issues for Forrester Research. "People want flexible access to content." Proof is Napster, of course, which represents a phenomenon Scheirer calls "unstoppable." Even if Napster is put out of business by the courts, he predicts that the frictionless distribution of digital content among the millions of Internet users will live on.

But Singh is betting heavily that DRM will prevail and, ironically, he thanks Napster. "Napster turned this whole issue into a CEO-level question. The very highest corporate officers now are looking into content management issues, and they want to protect their property."

That, says Singh, augurs wider use of DRM. "Here's the virtual cycle you will see: The more content a business puts online, the faster it will want to put still more content up, because it will see the economic benefits and users will see the benefits of gaining access to more content. That's why we are seeing an explosion here." —*Robert McGarvey*

Others in Digital Rights

Organization	Project
InterTrust Technologies (Santa Clara, Calif.)	Develops peer-to-peer distributed DRM technology
Reciprocal (New York)	DRM clearinghouse
Digimarc (Tualatin, Ore.)	Watermarking to embed an imperceptible code
Alchemedia (San Francisco)	"Clever Content" platform safeguards digital content

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JOSEPH ATICK

Biometrics

Visionics' Joseph Atick sees the wireless Web as key to widespread consumer adoption of biometric technologies.

In one sense, the field of biometrics—identifying individuals by specific biological traits—has already emerged. Large companies use fingerprint sensors for logging on to corporate networks, state driver's license authorities employ face recognition for capturing and storing digital photographs, and the first iris-scan-protected ATM in the nation was introduced in Texas in May 1999. Yet consumers have been reluctant to adopt the technology, and so far, it remains largely relegated to military and government applications.

But the emergence of another technology—the wireless Web—could soon change all that, according to Joseph Atick, president and CEO of Visionics, one of the leaders in face recognition technology. "Personal digital assistants (PDAs) and cell phones are becoming our portal to the world, our transaction devices, our ID and maybe one day our passport," says Atick. But entrusting these small gadgets with so much of our personal and financial information carries with it a great risk. "It is this need for security," Atick says, "that is going to drive biometrics."

And while the need for security is pushing the demand for biometric systems, other technology developments—increased bandwidth, new cell phones and handheld computers equipped with digital cameras—will create an infrastructure capable of putting biometrics into the hands of consumers. Visionics is taking advantage of this combination of need and infrastructure by developing tools to enable people to authenticate any transaction they make over the wireless Web using their own faces.

Even those in the industry who are skeptical of Atick's vision of a biometric-enabled wireless Web can't deny his ingenuity and ambition. At the age of 15, while living in Israel, Atick dropped out of school to write a 600-page physics textbook entitled *Introduction to Modern Physics*. "I was bored in school. I wanted to show the establishment I was serious about my interests," says Atick. "This book was my ticket to grad school." Remarkably, Stanford University accepted him at 16 into its graduate program, where he earned his master's degree in physics and PhD in mathematical physics.

After graduation, Atick applied his math skills to the study of the human mind. While heading the Computational and Neuroscience Laboratory at Rockefeller University, he sought to understand how the brain processes the abundance of visual information thrown at it by the environment. He and his colleagues discovered that the brain deals with visual information much as computer algorithms compress files. Because everyone has two eyes, a nose and lips, the brain extracts only those features that typically show deviations from the norm, such as the bridge of the nose or the upper cheekbones. The rest it fills in. "We soon realized there was tremendous commercial value to this process," says Atick. In 1994, he and colleagues Paul Griffin and Norman Redlich founded Visionics.

Based in Jersey City, N.J., Visionics develops and markets pattern-recognition software called FaceIt. In contrast to the main competing technology, which relies on data from the entire face, FaceIt verifies a person's identity based on a set of 14 facial features that are unique to the individual and unaffected by the presence of facial hair or changes in expression. In the past few years, the system has found success fighting crime in England and election fraud in Mexico.

In October, the company signed a merger agreement with Digital Biometrics, a Minnetonka, Minn.-based biometric systems engineering firm. Together they plan to build the first line of "biometric network appliances"—computers hooked to the Net with the capacity to store and search large databases of facial or other biometric information. The appliances, containing customers' identification data, can then receive queries from companies wanting to authenticate e-transactions. And while consumers will be able to access the system from a cell phone, PDA or desktop computer, Atick expects handheld devices to be the biggest

Others in Biometrics

Organization	Project
Viisage Technology (Littleton, Mass.)	Face recognition
Iridian Technologies (Marlton, N.J.)	Iris recognition
DigitalPersona (Redwood City, Calif.)	Fingerprint recognition
Cyber-SIGN (San Jose, Calif.)	Dynamic signature verification
T-NETIX (Englewood, Colo.)	Voice recognition

Photograph by NICK CARDILLICCHIO

market. Visionics is also working with companies in Japan and Europe to have FaceIt software installed on new Web-ready mobile devices so consumers can capture their own faces and submit encrypted versions over the Net.

Is that it for PINs and passwords? Atick predicts it will still be two to three years before PDA- and cell-phone-wielding consumers are likely to use biometrics instead. And as futuristic as his vision is, he is really striving toward something a bit old-fashioned. "Essentially, we are bringing back an old element of human commerce," says Atick—restoring the confidence that comes with doing business face to face. *—Alexandra Stikeman*

KAREN JENSEN

Natural Language Processing

The 1968 film *2001: A Space Odyssey* gave us a vision of the millennium based on the technological predictions of the day. One result: HAL 9000, a computer that conversed easily with its shipmates like any other crew member. The timing was off: In the real 2001, there's not a computer in the solar system as articulate as HAL.

But maybe it wasn't that far off. HAL's modern-day counterparts are catching up fast (sans the homicidal tendencies, one hopes). Already we have commercial speech recognition software that can take dictation, speech generation equipment that can give mute people voices and software that can "understand" a plain-English query well enough to extract the right answers from a database.

Emerging from the laboratories, moreover, is a new generation of interfaces that will allow us to engage computers in extended conversation—an activity that requires a dauntingly complex integration of speech recognition, natural-language understanding, discourse analysis, world knowledge, reasoning ability and speech generation. It's true that the existing prototypes can only talk about such well-defined topics as weather forecasts (MIT's Jupiter), or local movie schedules (Carnegie Mellon's Movieline). But the Defense Advanced Research Projects Agency (DARPA) is working on wide-ranging conversational interfaces that will ultimately include pointing, gesturing and other forms of visual communication as well.

Parallel efforts are under way at industry giants such as IBM and Microsoft, which see not only immediate applications for computer users who need to keep their hands and eyes free but also the rapid evolution of speech-enabled "intelligent environments." The day is coming when every object big enough to hold a chip actually has one. We'd better be able to talk to these objects because very few of them will have room for a keyboard.

Others in Language Processing

Organization	Project
Victor Zue (MIT Laboratory for Computer Science)	Conversational interfaces
Alexander I. Rudnicky (Carnegie Mellon)	Verbal interaction with small computers
Ronald A. Cole (University of Colorado)	Domain-specific conversational systems
BBN Technologies (Cambridge, Mass.)	Dialog agent

Microsoft Research's Karen Jensen is heading an effort to give machines the ability to grok human language.

Getting there will be a huge challenge—but that's exactly what attracts investigators like Karen Jensen, the gung-ho chief of the Natural Language Processing group at Microsoft Research. Says Jensen: "I can't imagine anything that would be more thrilling, or carry more potential for the future, than to make it possible for us to truly interact with our computers. That would be so exciting!"

Such declarations are typical of Jensen, who at 62 remains as exuberant about technology's promise as any teenager—and just as ready to keep hacker's hours. Indeed, Jensen was one of the first people Microsoft hired when it opened its research lab in 1991. Along with colleagues Stephen Richardson and George Heidorn, she arrived at the Redmond, Wash., campus from IBM's Thomas J. Watson Research Center, where they had worked on some of the earliest grammar-checking software, and immediately started building a group that now numbers some 40 people.

In Redmond, Jensen and her colleagues soon found themselves contributing to the natural-language query interface for Microsoft's Encarta encyclopedia and to the grammar checker that first appeared in Word 97. And now, she says, they've begun to focus all their efforts on a unique technology known as MindNet. MindNet is a system for automatically extracting a massively hyperlinked web

Photograph by KAREN MOSKOWITZ

of concepts from, say, a standard dictionary. If a dictionary defines "motorist" as "a person who drives a car," for example, MindNet will use its automatic parsing technology to find the definition's underlying logical structure, identifying "motorist" as a kind of person, and "drives" as a verb taking motorist as a subject and car as an object. The result is a conceptual network that ties together all of human understanding in words, says Jensen.

The very act of putting this conceptual network into a computer takes the machine a long way toward "understanding" natural language. For example, to figure out that "Please arrange for a meeting with John at 11 o'clock" means the same thing as "Make an appointment with John at 11," the computer simply has to parse the two sentences and show that they both map to the same logical structures in MindNet. "It's not perfect grokking," Jensen concedes. "But it's a darn good first step."

MindNet also promises to be a powerful tool for machine translation, Jensen says. The idea is to have MindNet create separate conceptual webs for English and another language, Spanish, for example, and then align the webs so that the English logical forms match their Spanish equivalents. MindNet then annotates these matched logical forms with data from the English-Spanish translation memory, so that translation can proceed smoothly in either direction.

Indeed, says Jensen, who is now in the process of passing on the leadership of the group to the younger generation, MindNet seems to tie together everything they've been doing for the past nine years: "All we see is doors opening. We don't see any closing!" —*M. Mitchell Waldrop*

Others in Microphotonics

Organization	Project
Eli Yablonovitch (UCLA)	Photonic crystals for optical and radio frequencies
Susumu Noda (Kyoto University, Japan)	Optical integrated circuits
Axel Scherer (Caltech)	Optical switches, waveguides and lasers
Nanovation Technologies (Miami)	Integrated devices for telecom
Clarendon Photonics (Boston)	Filters for WDM

JOHN JOANNOPOULOS

Microphotonics

Light bounces off the small yellow square that MIT physics professor John Joannopoulos is showing off. It looks like a scrap of metal, something a child might pick up as a plaything. But it isn't a toy, and it isn't metal. Made of a few ultrathin layers of non-conducting material, this photonic crystal is the latest in a series of materials that reflect various wavelengths of light almost perfectly. Photonic crystals are on the cutting edge of microphotonics: technologies for directing light on a microscopic scale that will make a major impact on telecommunications.

In the short term, microphotonics could break up the logjam caused by the rocky union of fiber optics and electronic switching in the telecommunications backbone. Photons barreling through the network's optical core run into bottlenecks when they must be converted into the much slower streams of electrons that are handled by electronic switches and routers. To keep up with the Internet's exploding need for bandwidth, technologists want to replace electronic switches with faster, miniature optical devices, a transition that is already under way *(see "The Microphotonics Revolution,"* TR *July/August 2000)*.

Because of the large payoff—a much faster, all-optical Internet—many competitors are vying to create such devices. Large telecom equipment makers, including Lucent Technologies, Agilent Technologies and Nortel Networks, as well as a number of startup companies, are developing new optical switches and devices. Their innovations include tiny micromirrors, silicon waveguides, even microscopic bubbles to better direct light.

But none of these fixes has the technical elegance and widespread utility of photonic crystals. In Joannopoulos' lab, photonic crystals are providing the means to create optical circuits and other small, inexpensive, low-power devices that can carry, route and process data at the speed of light. "The trend is to make light do as many things as possible," Joannopoulos says. "You may not replace electronics completely, but you want to make light do as much as you can."

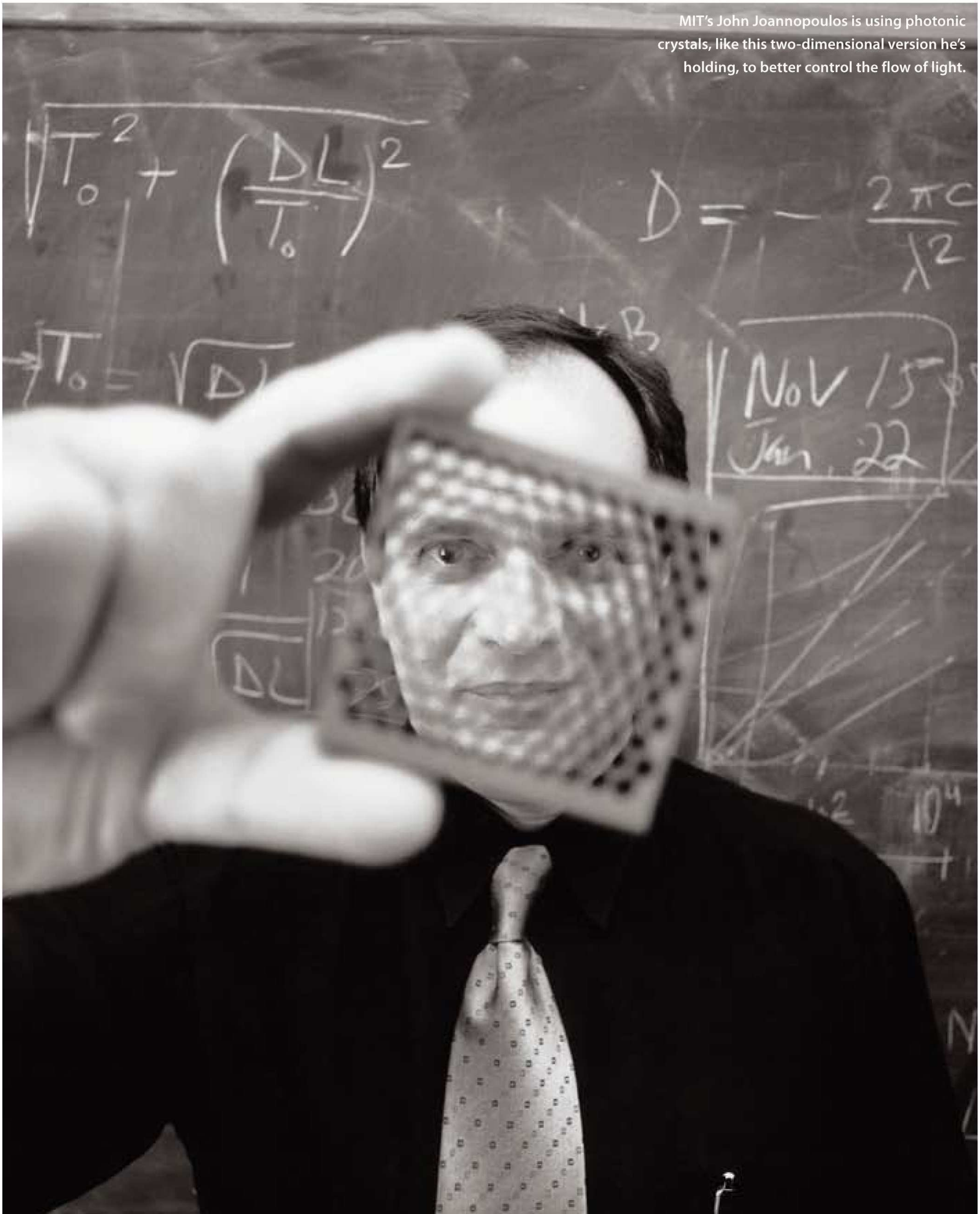
Conceived in the late 1980s, photonic crystals are to photons what semiconductors are to electrons, offering an excellent medium for controlling the flow of light. Like the doorman of an exclusive club, the crystals admit or reflect specific photons depending on their wavelength and the design of the crystal. In the 1990s, Joannopoulos suggested that defects in the crystals' regular structure could bribe the doorman, providing an effective and efficient method to trap the light or route it through the crystal.

Since then, Joannopoulos has been a pioneer in the field, writing the definitive book on the subject in 1995: *Photonic Crystals: Molding the Flow of Light*. "That's the way John thinks about it," says MIT materials scientist and collaborator Edwin Thomas. "Molding the flow of light, by confining light and figuring out ways to make light do his bidding—bend, go straight, split, come back together—in the smallest possible space."

Joannopoulos' group has produced several firsts. They explained how crystal filters could pick out specific streams of light from the flood of beams in wavelength division multiplexing, or WDM, a technology used to increase the amount of data carried per fiber *(see "Wavelength Division Multiplexing,"* TR *March/April 1999)*. The lab's work on two-dimensional photonic crystals set the stage for the world's smallest laser and electromagnetic cavity, key components in building integrated optical circuits.

But even if the dream of an all-optical Internet comes to pass, another problem looms. So far, network designers have found ingenious ways to pack more and more information into fiber optics, both by improving the fibers and by using tricks like WDM. But within five to 10 years, some experts fear it won't be possible to squeeze any more data into existing fiber optics.

The way around this may be a type of photonic crystal recently created by Joannopoulos' group: a "perfect mirror" that reflects specific wavelengths of light from every angle with extraordinary efficiency. Hollow fibers lined with this reflector could carry up to 1,000 times more data than current fiber optics—offering a solution when glass fibers reach their limits. And because it doesn't absorb and scatter light like glass, the invention may also eliminate the expensive signal amplifiers needed every 60 to 80 kilometers in



MIT's John Joannopoulos is using photonic crystals, like this two-dimensional version he's holding, to better control the flow of light.

Photograph by JOHN SOARES

With his "aspect-oriented" approach, Xerox PARC's Gregor Kiczales is making computer programs easier to write and maintain.

today's optical networks *(see "Blazing Data,"* TR *November/December 2000).*

Joannopoulos is now exploring the theoretical limits of photonic crystals. How much smaller can devices be made, and how can they be integrated into optical chips for use in telecommunications and, perhaps, ultrafast optical computers? Says Joannopoulos: "Once you start being able to play with light, a whole new world opens up." —*Erika Jonietz*

Others Untangling Code

Organization	Project
Mehmet Aksit (University of Twente, the Netherlands)	Composition filters
Karl Lieberherr (Northeastern University)	Adaptive programming
IBM Research (Yorktown Heights, N.Y.)	HyperJ system for Java programming
Mira Mezini (Univ. of Siegen, Germany)	Enhancing modularity and reusability of A-O software

GREGOR KICZALES

Untangling Code

Pity software engineers. With the touch of a button, their programs let us make global fixes in a long text, say, or a spreadsheet, yet programmers often need to correct their own work one tedious line at a time. That irony isn't lost on Gregor Kiczales, principal scientist at Xerox's Palo Alto Research Center (PARC) and professor at the University of British Columbia in Vancouver—and he has a fix in mind. Kiczales champions what he calls "aspect-oriented programming," a technique that will allow software writers to make the same kinds of shortcuts that those of us in other professions have been making for years.

One such "crosscutting" capability is logging—the ability to trace and record every operation the application performs. Since any given command might touch down on functionally unrelated areas of the code, programmers now must make a rule, such as: "When adding a new function to this application, always put a trace statement in." Of course, the rule works only if people remember to follow it.

Other crosscutting capabilities include security and synchronization—the ability to make sure that two users don't try to access the same data at the same time. Both require programmers to write the same functionality into many different areas of the application. Even a modest-sized application can easily present 100 crosscutting issues.

Programmers try to track these instances of repetition, so that when a capability needs to be changed or upgraded, it can be done uniformly throughout the program. But keeping track of crosscutting concerns is an error-prone process. Forget to upgrade just a few of these instances, and your code starts collecting bugs. "We're forced to keep track of everything in our heads," says Kiczales.

Kiczales' proposed solution is to create a new category within a programming

Photograph by MARK GILBERT

language called an "aspect." Aspects allow programmers to write, view and edit a crosscutting concern as a separate entity. Once the programmer is happy with it, a single keystroke will weave the aspect into the code wherever it is needed. It's a smart, intuitive, neat solution to an old problem. And what's good for programmers is good for the rest of us: Widespread adoption of aspects holds out the promise of less buggy upgrades, shorter product cycles and, ultimately, better and less expensive software.

The idea of aspects has been around for many years and with many different names. It's called "adaptive programming" at Northeastern University, "subjective programming" at IBM, "composition filtering" at the University of Twente in the Netherlands and "multidimensional separation of concerns" elsewhere. But unlike these other research projects, Kiczales and his team at PARC have taken the concept out of the lab and into the real world by incorporating the idea of aspects into a new extension of the programming language Java. The beta version of this extension (called AspectJ) is available for free at www.aspectj.org, and Kiczales plans to make release 1.0 ready by June. "Major changes in programming methodology can take 30 years to gain widespread acceptance," he says. Making aspects an extension to an existing standard should, he predicts, "cut the cycle by 15 or 20 years."

While Kiczales admits the tools are still a little raw, there are nevertheless about 500 users of AspectJ today—most of them finding existing tools inadequate for creating long, complicated programs in Java. Some have already found AspectJ so solid that they've used it in production. One of these is Checkfree.com, a company that makes software for automatic bill payment. Checkfree sells both C++ and Java versions of the software. Rich Price, senior engineer, estimates that AspectJ allowed his team to implement an important crosscutting capability in the Java version in four programmer-hours, whereas the C++ team, with no aspect-oriented programming tools at their disposal, took two programmer-weeks to do the same thing. Using aspects, he says, "I make one change, in one place, and it gets woven in where it needs to be. I love that."

By folding their ideas into a practical Java extension, Kiczales and his team hope to make aspects part of the vernacular of programming languages. "AspectJ lets programmers work more quickly and at a higher design level," says Kiczales. "We've learned that crosscutting concerns are actually not hard to work with—once you have the proper programming support." —*Claire Tristram*

JORDAN POLLACK

Robot Design

Robot builders make a convincing case that in 2001, robots are where personal computers were in 1980—poised to break into the marketplace as common corporate tools and ubiquitous consumer products performing life's tedious chores. One big obstacle remains: It is expensive to design and make robots smart enough to adapt readily to different tasks and physical environments, the way human beings do.

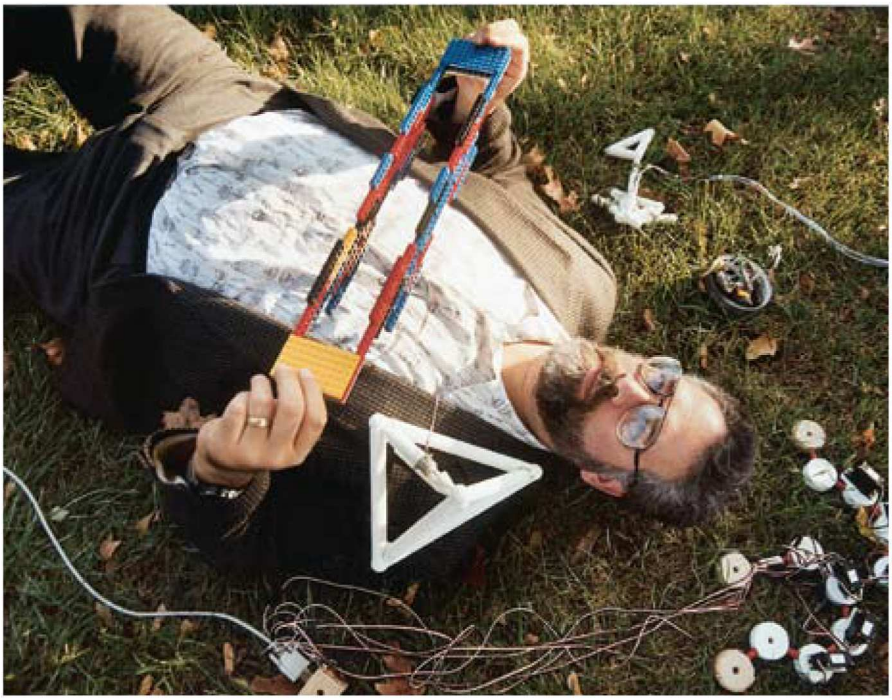
That's the reason why robotics have, so far, found a commercial niche only in simple and highly repetitive jobs, such as working on an automotive assembly line, or mass-producing identical items, such as toys. The challenge for builders of robots is to build more complexity into them without the huge investment of custom-tailoring each robot for a different task.

One promising approach is to fully automate the design and manufacture of robotics by deploying computers to conceive, test and even build the configurations of each robotic system: in short, to use robots to build robots. Last year, in a cramped lab at Brandeis University in Waltham, Mass., Jordan Pollack demonstrated how this automated robotic design and manufacturing might work.

Pollack, an associate professor of computer science, together with postdoc Hod Lipson, directed a computer to design a moving creature using a limited set of simple parts: plastic rods, ball joints, small motors and a "brain" (neural network). The computer—using an algorithm inspired by biological evolution—"evolved" hundreds of generations of potential designs, killing off the sluggish and refining the strong. Eventually, several of the fastest and fittest came to life,

Others in Robot Design

Organization	Project
Sarcos (Salt Lake City, Utah)	Robots for industry, medicine, Hollywood
iRobot (Somerville, Mass.)	Household communications robot
Humanoid Interaction Lab (Tsukuba, Japan)	Interactions between humanoid robots and humans
MIT Artificial Intelligence Lab (Cambridge, Mass.)	Machine learning, robot legs, faces
Robotics Institute (Carnegie Mellon)	Mobile robots and face recognition



Brandeis' Jordan Pollack with some of his "creatures" designed by robots.

Photograph by JOHN GOODMAN

manufactured in a rapid-prototyping machine. Pollack and Lipson snapped on the motors, and the creatures moved.

"I think the important point of our coevolutionary design and automated manufacturing for robotics is to get small-quantity production to be economical," Pollack says. He predicts that the evolutionary approach to robot building could lead to the first cheap industrial robots in five to 10 years. "If we are successful, we could see an industry within a decade which makes low-quantity custom machinery worth more than it costs to make."

For now, Pollack's "automated" process still takes plenty of human intervention and money: Pollack and his colleague wrote the computer program and spent $50,000 on the human-built fabricating device. Still, the team's advance, reported last August in the journal *Nature,* garnered wide publicity. "The importance is symbolic," says Hans Moravec, principal research scientist at the Robotics Institute at Carnegie Mellon University in Pittsburgh. "You have systems that develop robots out of thin air, not by humans. In the future, there will be real robots designed that way."

Pollack's design and manufacturing methods have plenty of competition. Academic and industrial labs around the world are busy building new generations of robots. Within this decade, experts predict a steady evolution in commercial utility robots: robots that can clean floors and pick up things. "There will be a mass market for robots," suggests George Bekey, founder of the robotics lab at the University of Southern California in Los Angeles. "This next decade will be the decade of the robot."

Before robots reach out into the everyday world of business and the household, though, they will need their own version of Moore's Law: becoming dramatically more affordable and powerful over time. In spite of intriguing experiments such as Pollack's, designing even relatively simple robots is a painstaking task. In Japan, for example, Honda has spent over 14 years building a humanoid robot able to walk, open a door and navigate stairs.

A walk around Pollack's lab suggests, perhaps, a better way to design robots. On a workbench sits one example of his computer-designed and computer-buildable machines; it moves eerily like an inchworm. Pollack trims excess plastic from a newly fabricated plastic-rod machine, oblivious to the shavings collecting on his shirt and around his chair. In a few years Pollack may well evolve a cheap robot able to sweep those shavings off the floor. *—David Talbot*

Others in Microfluidics

Organization	Project
Aclara BioSciences (Mountain View, Calif.)	Genomics and drug screening
Caliper Technologies (Mountain View, Calif.)	DNA, RNA and protein assays
Cepheid (Sunnyvale, Calif.)	DNA analysis
Micronics (Redmond, Wash.)	Diagnostics and chemical analysis
TECAN (Hombrechtikon, Switz.)	Drug discovery

STEPHEN QUAKE

Microfluidics

The forces of physics move oceans, mountains and galaxies. But applied physicist Stephen Quake uses them to manipulate things on a vastly reduced scale: tiny volumes of fluids thousands of times smaller than a dewdrop. Microfluidics, as Quake's field is called, is a promising new branch of biotechnology. The idea is that once you master fluids at the microscale, you can automate key experiments for genomics and pharmaceutical development, perform instant diagnostic tests, even build implantable drug-delivery devices—all on mass-produced chips. It's a vision so compelling that many industry observers predict microfluidics will do for biotech what the transistor did for electronics.

Quake's 11-person lab at Caltech is not the only outfit bent on realizing this vision. Over the past decade or so, scores of researchers have set out to build microscale devices for many of the basic processes of biological research, from sample mixing to DNA sequencing. But many of those groups have run into roadblocks in developing technology that can be generalized to a broad range of applications and would allow several functions—such as sample preparation, DNA extraction and detection of a gene mutation—to be integrated on a single chip. Moreover, some of the manufacturing approaches involved, particularly silicon micromachining, are so expensive that experts in the field question whether products relying on these techniques could ever be economical to manufacture.

Quake's group is one of several now working their way around these obstacles. Last spring, the team unveiled a set of microfabricated valves and pumps—a critical first step in developing technology general enough to work for any microfluidics application. And to make microfluidic devices cheaper, Quake and others are casting them out of soft silicone rubber in reusable molds, using a technique called "soft lithography." The potential payoff of these advances is huge: mass-produced, disposable microfluidic chips that make possible everything from drug discovery on a massive scale to at-home tests for common infections.

Because microfluidics is so promising and yet so technically frustrating, expectation and hype have sometimes outpaced the development of viable technology. Yet Quake and his group have consistently turned out elegant devices that actually work. First was a microscale DNA analyzer that operates faster and on different principles than the conventional, full-sized version, then a miniature cell sorter and most recently, those valves and pumps, described last April in the journal *Science*. All this while regularly publishing important findings on the basic physics of biological molecules.

If Quake seems adept at straddling fields—in this case science and technology—perhaps it's because that's exactly the sort of challenge he has long craved. Even as an undergraduate at Stanford University, where he earned bachelor's and master's degrees simultaneously in only four years, Quake worried that physics was "somewhat finished" as an experimental science, that it was hard to find the field's frontiers. A pioneer at heart, Quake started looking to tackle questions that lay at the boundaries between disciplines. As he recalls: "It was completely obvious, even to an outsider, that biology was going through this period of incredible growth and intellectual excitement, and there were going to be big questions asked and answered, and the frontiers were advancing at a tremendous rate in all directions."

After Quake finished his doctorate in theoretical physics at Oxford University,

Caltech's Stephen Quake has set his sights on the microscale, building tiny disposable devices that could revolutionize biotechnology.

he went back to Stanford as a fellow working on the physics of DNA. When Caltech's applied physics department hired him in 1996, Quake says, "it was an experiment for them"—he was the first faculty member in the department with a biological bent. So far, the experiment seems to be going smoothly; this past summer, at only 31, Quake got tenure.

Quake's inventions are also thriving in industry, through a startup called Mycometrix. Founded in 1999 by Quake, two of his college classmates and a consultant, the South San Francisco-based company has licensed all of Quake's microfluidics patents from Caltech. When *TR* went to press, the company was planning to deliver its first microfluidic devices to selected university researchers and industry partners by the end of 2000, and was hoping for a commercial release by the end of this year or early 2002. The competition will be intense. Several startups and even electronics giants like Hewlett-Packard and Motorola are getting in on the game. But to date, only one of Mycometrix's competitors has brought a microfluidic product to market.

Although Quake's work is rapidly flowing into the commercial marketplace, it's still the very early stages of science and technology development that interest him the most. And though he has built quite a reputation as a technologist, he hopes soon to focus more of his attention on some of the most pressing questions in basic biology: How do the proteins that control gene expression work? How can you do studies that cut across the entire genome? "Now that we've got some pretty neat tools," Quake says, "we're going to try and do some science with them." Quake's ability to work in areas from basic research to hot commercial markets make him a prototypical innovator. And the same versatility makes microfluidics a field to pay close attention to in the next few years. *—Rebecca Zacks*

Photograph by MICHAEL GRECCO

Handheld Heaven

For Mehul Khakhkhar, a high school sophomore who lives near Chicago, the Palm Pilot handheld computer is much more than a personal organizer; it's a portable scientific instrument that can record pH, temperature and the oxygen content of the pond in his school's courtyard. Using a special adapter that snaps onto the bottom of the Pilot and a program that simulates an electronic notebook, Khakhkhar can take a series of measurements over several days and graph the changes. "It's actually more convenient than writing all the data down in a notebook with a pencil," says the honors biology student. "It's more fun."

And more useful. Using the built-in infrared interface, Khakhkhar can beam his data to his classmates. And he can upload his results to his family's desktop computer when it comes time to write his report. He also uses the handheld computer to take notes and keep track of assignments.

Other students in Khakhkhar's high school district are using Palm computers to track their food consumption and physical exercise, creating a comprehensive fitness profile. Erin Singleterry, 15, downloaded a Spanish/English dictionary to help her with her study of *español.* The electronic dictionary is a lot easier than a paper one, she says, "because you can write in the word and [the computer] finds it."

"We have over 400 teachers across our three schools in this program," says Darrell Walery, director of technology for high school district 230. Teachers use Palm computers with two of their classes, where each student either purchases or leases their own handheld device for the year. "This is a chance to give the students a really powerful handheld computer that they can use throughout the day," says Walery.

PHILIPPE WEISBECKER

The original Palm handheld organizers weren't designed with these sorts of uses in mind. No, the Palm was created to be a simple way for people to carry around their calendar, address book and to-do lists. And it's been so successful that more than 8.7 million Palm organizers have been sold. But over the past year, computers running the PalmOS operating system have stepped over some kind of threshold. Instead of being simple organizers, the PalmOS is now widely regarded as the world's next major computing platform—a platform that's specially optimized for ubiquitous mobile computing.

This transformation has been driven by Palm's third-party developers. In fact, Palm and 3Com have spent much of the past few years trying to sell the organizers for enterprise computing—that is, vertical applications used by large organizations—rather than trying to broaden the Palm's appeal throughout our society.

On the software front, some of the most exciting programs for the Palm are those that take advantage of its "always with you" characteristic. The great power of the Internet is the wealth of information that's available at your fingertips. The great problem with the Internet is that it ties you to your desktop. These new programs and services aimed at Palm users solve this problem by packaging up the Internet and other data services and making them available offline.

One little program that brought this all home to me is an electronic bus-and-train application called Commute. I discovered Commute one day when I was sitting in a coffee shop with a friend in New York City. I asked him if he could stay for dessert; he took out his Palm, clicked a single button, and told me that his train left in 25 minutes. The program consults the PalmOS clock and then displays only the scheduled

trains and buses that have not already left.

Some new applications combine the Palm's ubiquitous presence with the power of Internet access. Two examples are AvantGo and Vindigo. Both programs suck down data from the Internet every time you synchronize your PalmOS device with a desktop computer. AvantGo is great for news junkies: I use it to download the front page of *The New York Times* and *The Wall Street Journal*, and half a dozen other news-oriented Web sites every morning, giving me several hundred pages of reading material for my morning bus ride. Since I've started using AvantGo, I've pretty much stopped taking printed newspapers or magazines on the bus: it's far easier for me, and less intrusive to my seat mates, to read from the tiny screen than to try to unfold the newspaper. (The big disadvantage is the quality of the black-and-white screen: unless you are in a brightly lit room, it's pretty muddy.)

Vindigo does the same thing for movies and restaurants, automatically downloading schedules and reviews. You can search by movie and get a list of theaters and times. Alternatively, you can click on the name of your favorite revival theater, and get a list of what it is playing that night. Vindigo also has a built-in map: you simply tell the program the nearest pair of cross streets, and it gives you walking directions to your destination.

The second part of the Palm's transformation has been driven by a number of hardware vendors, most notably Handspring—the company formed by a pair of Palm's founders who left shortly after Palm's acquisition by 3Com *(see "That's Not How* My *Brain Works...,"* TR *July/August 1999*). Handspring's PalmOS device, called the Visor, comes in an array of different colors, as any good piece of consumer electronics should. But what's really innovative is the matchbook-sized expansion slot (called the "springboard") on the back—a feature that invites tinkering and customization by third-party developers.

They're not just for appointment books anymore. New software and hardware add-ons are plugging the PalmOS devices into the Internet.

PHOTOGRAPH BY FURNALD/GRAY

It's been less than a year since the Visor started shipping, and already companies have delivered Visor modules that turn this PalmOS-based computer into a digital camera, a two-way pager and a universal remote control. But the most exciting module comes from Handspring itself: the VisorPhone. This clever add-on is a complete cellular telephone that drops into the backside of the Visor. To place the call, just look up somebody's phone number in the PalmOS address book and click the "dial" button. Or you can just tap the number on the Visor's screen.

There's a simple motivation behind the VisorPhone, says Chris Cadwell, Handspring's director of marketing for communication products. Cell phones are arguably one of the most successful consumer products of all time. One reason is ease of use. "Everybody thinks that the cell phone is easy," says Cadwell. That's deceptive, though; the illusion of ease of use arises from the fact that most people use their cell phones in only the most rudimentary fashion, by punching buttons on a keypad to place a call. But in fact, he says, cell phones are extraordinarily complicated devices to master. Few people use the advanced capabilities of most cell phones—features like phone books that can store a hundred names, three-way calling, and text messaging—because most people can't figure out how to use the typical cell phone's user interface.

The VisorPhone does away with most of these problems by eliminating the cell phone's traditional user interface and instead simply integrating the phone's telephony features in with the other PalmOS functions. The result is a cell phone as easy to use as a Palm-based computer. That's a huge benefit for people who rely heavily on cell phones but who are not gadget geniuses—in other words, the majority of the cell phone-using population.

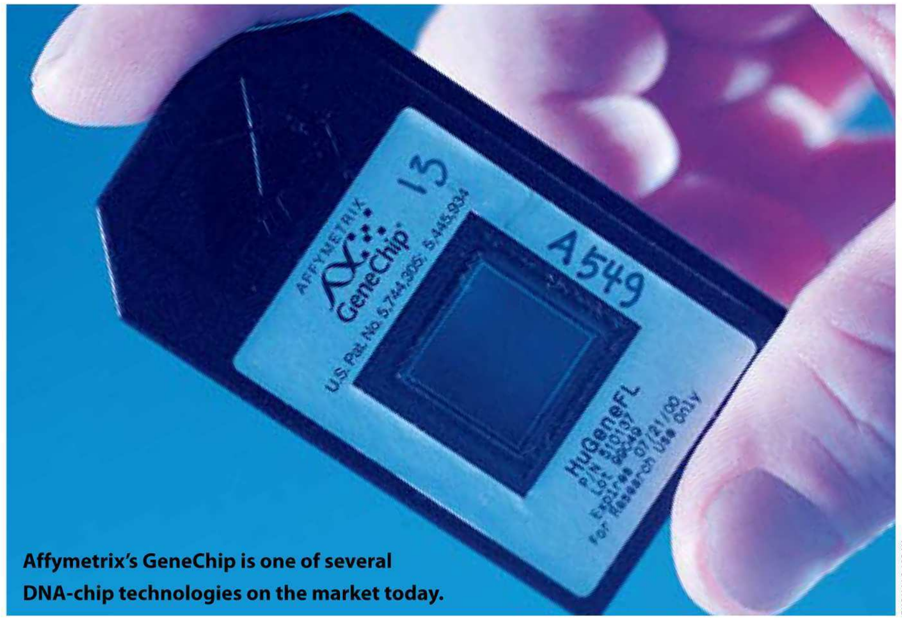
To be sure, this isn't the first time that a company has tried to fuse a PalmOS-based computer with a cellular telephone. Qualcomm tried that trick last year, when the company introduced the pdQ smartphone—a device that belly-flopped in the market. "The difference between us and Qualcomm," says Cadwell, "is that they are a phone company that added a Palm to a phone. We integrated a voice communications device into the Visor." And Handspring has blended the two devices seamlessly. Another big difference is price: A Visor and VisorPhone can be purchased together for less than $450, about half the price of the Qualcomm phone.

Unfortunately, all of these devices have an Achilles' heel: an utter lack of security. The PalmOS has no memory protection and no safeguards against viruses or hostile code. That represents a serious problem. After all, a Palm VII, with its wireless link, can initiate stock trades. A VisorPhone can make calls to 900 numbers. Palm says that it intends to address this issue, but any workable solution seems years in the future.

Nevertheless, if the VisorPhone is successful, it could be the start of an important new trend: the morphing of PalmOS from an operating system that's used by handheld organizers into an operating system that's used by a wide class of digital devices. After all, there's a learning curve associated with any user interface—so why should cell phones, microwave ovens and VCRs all have different ones, each requiring separate mastery? We live in a digital Babel; the PalmOS user interface could soon become the *lingua franca* for many of these devices. ◊

Simson Garfinkel writes on information technology and its impact. He is author of Database Nation *(O'Reilly, 2000).*

VISUALIZE



Affymetrix's GeneChip is one of several DNA-chip technologies on the market today.

FURNALD/GRAY

DNA Chips

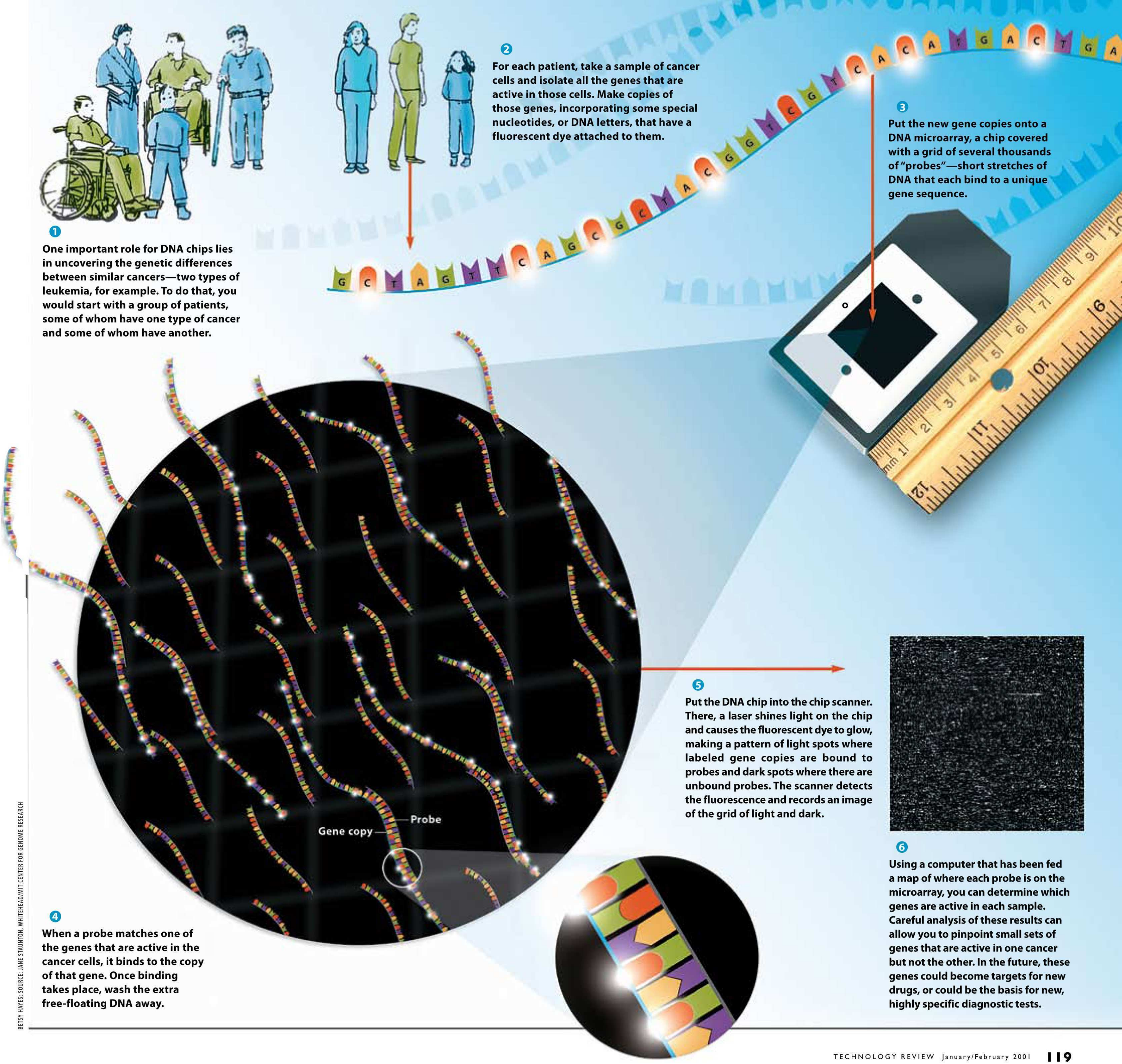
They can analyze thousands of genes at a time. Here's how

IN THE PAST FEW YEARS, THE PROMISES OF BIOTECHNOLOGY—NEW knowledge of health and disease, better diagnostics and treatments—have been driven ever closer to fruition by an unprecedented torrent of biological data flowing from research labs. One of the key technologies generating this critical new wealth of information is a postage-stamp-sized slide of glass or plastic called a DNA microarray or, more colloquially, a DNA chip.

DNA chips made their big splash in 1996 when Santa Clara, Calif.-based Affymetrix introduced the first commercial version, which the company dubbed GeneChip. Affymetrix uses light-sensitive chemical reactions to grow a grid-like pattern of as many as 400,000 short DNA strands, called probes, on a glass wafer. Since each probe can bind to a different gene sequence in a sample of DNA, the chips allow researchers to perform what once would have been thousands of separate experiments all at the same time. Researchers in biotechnology, pharmaceuticals and the Human Genome Project were dazzled by the possibilities: new understanding of the role genes play in heart disease or antibiotic resistance, tools for prenatal or infection diagnosis that incorporate all the genes of interest on a single chip, massive-scale automated screening of potential drugs.

Today, dozens of companies provide DNA-chip products and services. With the development of new ways to fabricate the chips, researchers now have the option of buying ready-made chips or building their own customized chips right in the lab. And some of the earliest hopes about the technology—particularly that it would help reveal the genetic underpinnings of cancer—already show signs of fulfillment. Just last year, for example, researchers at the Stanford University School of Medicine used DNA chips to discover two genetically distinct classes of disease within a type of lymphoma previously classified as one cancer; since a patient's chance of survival depends significantly on which of the two subtypes he or she has, understanding the differences between the two could lead to better-tailored treatments.

To show just how DNA chips work, *TR* walks you though a hypothetical cancer experiment, step by step. ◊



BETSY HAYES; SOURCE: JANE STAUNTON, WHITEHEAD/MIT CENTER FOR GENOME RESEARCH

The Kids Are All Right Online

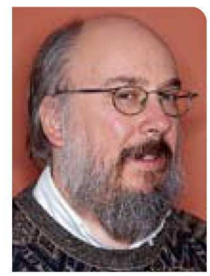
A WORKING-CLASS BLACK woman lingered after I spoke about youth and digital media last year at Detroit's Wayne State University. She pushed her way through the crowd to ask a simple question: "Will my boy be all right?"

Her adolescent son spent a great deal of time online, talking with friends, building his home page, playing computer games, doing his homework. She had heard conflicting reports—teachers claiming Net access fostered educational growth, and media reformers warning about teens "running amok" on the Net. After the Columbine shootings, the moral panic about "growing up online" and the shooters' hate-spewing Web sites dominated media coverage. And now, like so many other American parents, she was worried that she was wrong to let her son explore cyberspace when she knew so little about computers herself.

As the director of MIT's new Comparative Media Studies Program, I had been called months earlier to testify before the U.S. Senate Commerce Committee hearings on "marketing violence to youth." As the father of a 19-year-old son, I already knew how contemporary adolescents were using digital media to expand their social networks and how important those links could be, especially for outcasts or kids at risk. Trying to better understand youth perspectives, I launched a tour of American high schools and monitored teen Web sites. Those experiences convinced me that many of our kids are going to be all right, not in spite of the fact that they are growing up online but *because* of it.

American adolescence is an emotional battleground: Children struggle to define who they are and how they fit into the adult world, adults struggle between desires to push them from the nest and to clutch them to our breasts. Teens need a safe space to take their first steps toward adulthood, to find their political voices and to bond with a community beyond the immediate family. For many of our children, the Web has become such a place. The Web hasn't made teens lonely; it offers a way to connect with others like themselves, who share their values and who care about what they have to say. Outcasts need such a space even more than kids who get strokes from their parents, teachers and coaches.

A teen chat room can be as brutal as a locker room, but the Web offers more places to find yourself than a high school's long and lonely hallways.



PHOTOGRAPH BY FURNALD/GRAY

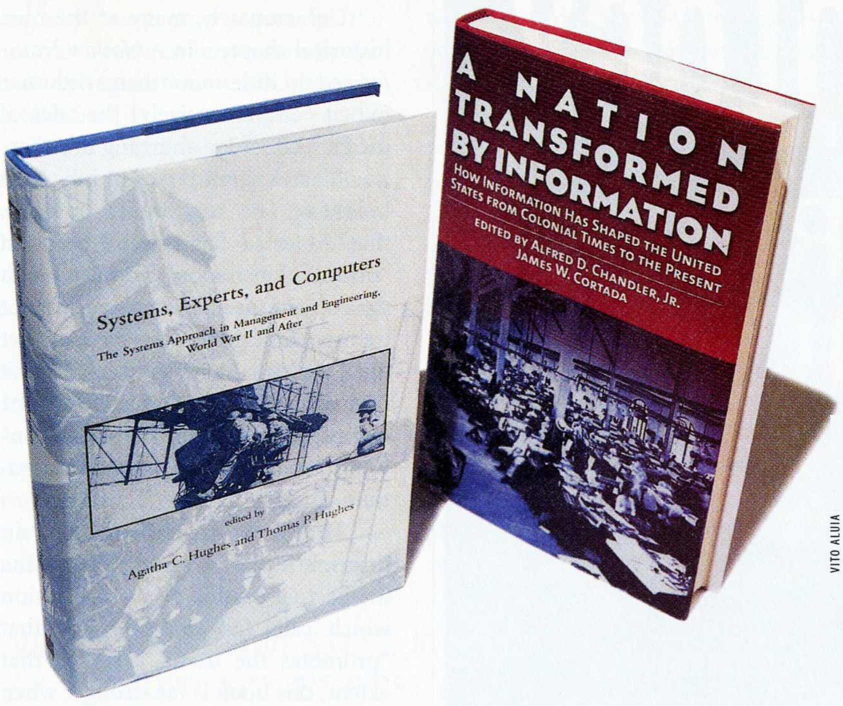
Contrary to the ominous news images of teen Web sites, teens themselves often describe the Web as a utopian space, a refuge from divorced parents, economic hardship, crowded classrooms, intolerant teachers and hostile peers. As one raver said of his site, "This place, my little home on the Web, was designed out of the desire to have a place to go when I want to feel like there are no problems, no worries, no stress and no violence in or around my life." Another girl named her Web site "Palisades," explaining the word's relevance: "A strong fence made of stakes driven into the ground for defense. Palisades is a place where I can feel free to express myself without fear of being torn down…. Within the Palisades you will find the real me."

Many kids feel they have little say in their real-world environments, and so they value the Web as their own world—where they set the rules. As one teen explained, "It's the only thing I have total control over, and I love it." For some, the idea of a culture created and defined by adolescents may evoke images straight from *Lord of the Flies*. Indeed, a teen chat room can be as brutal as a high school locker room. Still, the Web offers more places to hide and more places to find yourself than a school's long and lonely hallways. The Internet expands the number of potential social contacts for isolated teens. In a small-town school, there may be only one goth or openly gay student. On the Web, there are thousands, if not millions.

But a kid's ability to find acceptance and affirmation through this social network depends on relatively unfettered Net access. The minute that adults police the Web, teens are back in a realm where self-revelation carries risks. Many of the filtering programs on school computers, for example, block access to any site referring to homosexuality, whether or not the content of the site is sexually explicit, cutting off a lifeline for gay, lesbian and bisexual teens.

Slashdot columnist Jon Katz has described young people as "ground zero" in the digital revolution, at once the force for cultural transformation and the group in which the defining struggles will take place. Kids know the digital revolution demands a battle against adult attempts to regulate youth expression. The Web has given them a taste of freedom and a glimpse of another world. Their desire to dwell in cyberspace can't be reduced to Internet addiction, emotional withdrawal or any other reformist cliché. If teens would rather be online, maybe it's because their everyday lives suck. If we want to make sure they will be all right, we shouldn't block their access; we should use their online world as a model to reform the real-world institutions that are failing them. ◊

Henry Jenkins is co-editor of From Barbie to Mortal Kombat: Gender and Computer Games *(MIT Press, 1998).*



VITO ALUIA

BOOK REVIEWS | MICHAEL SCHRAGE

Customers as Innovators

Two anthologies argue that early adopters often drive innovation as much as brilliant inventors do.

A PECULIAR ASYMMETRY warps most histories of technological innovation. The innovators are treated as visionary heroes, while the users and consumers of the innovations are treated as a faceless marketplace that finally grasped the importance of the proffered invention.

Everybody knows about Apple Computer's Wozniak and Jobs. Yet who's written the profiles of Apple's first thousand customers? Yes, Intel's Noyce, Hoff and Faggin pioneered the microprocessor. But who were the early adopters that gave Intel insight into what that chip could really do? Dan Bricklin and Bob Frankston revolutionized personal computing software with the invention of VisiCalc. But who knows what 50 financial services firms first transformed themselves by using that software spreadsheet in unexpected ways?

Of course, these innovations today would be described as brilliant failures had they failed to catch on. But since it's seemingly so much easier to describe the achievements and personalities of the innovators than the character and risks taken by the innovation adopters, history is accordingly skewed.

That's why *A Nation Transformed by Information* and *Systems, Experts and Computers* represent a healthy change of historical perspective and pace. These university press anthologies are filled with details—some pieces excruciatingly so—of how, in fact, innovation is the relentless coevolutionary synthesis of innovator and adopter. Indeed, one could make a very powerful case that, at the earliest stages of a new technology or technique, the brilliant customer is at least as important as the brilliant innovator.

For example, the story of Samuel F. B. Morse's telegraph is fairly well known. How the railways and the postal service ultimately adopted telegraphy in their own infrastructures is not. In fact, according to historian Richard R. John's essay in *A Nation Transformed*, the railways were initially quite slow to use the telegraph to coordinate their operations. Ultimately, to speed things up, Western Union and telegraphy cut sweetheart deals with the railroads, thus ensuring for the telegraph companies not only a major customer but an infrastructure of their own. The rights-of-way of railroads and telecommunications thus coevolved.

Chandler and Cortada's *A Nation Transformed* is chock-full of the stories of such relationships. Chandler, the *éminence grise* of business historians, does a superb job of finding the common themes in this dense survey of America's information/innovation landscape.

The chapter by JoAnne Yates, on business adoption of information technology during the industrial age, is particularly good. As technology became a battleground between the Tayloresque "scientific management" school and the Mayoesque "human relations" managerial movement, distinctions between "back office" management and "customer touch" began to be instantiated in hardware and office designs. What you find is the clear sense that customers were even more innovative than vendors. Indeed, the notion that persistent innovators finally persuaded recalcitrant markets to adopt their wares is more mythical than historical. Many customers in many market segments drove innovation as much as they procured it.

BOOK: *A Nation Transformed by Information: How Information Has Shaped the United States from Colonial Times to the Present*
EDITORS: Alfred D. Chandler Jr. and James W. Cortada
PUBLISHER: Oxford University Press, $39.95

BOOK: *Systems, Experts and Computers: Systems Approach in Management and Engineering, World War II and After*
EDITORS: Agatha C. Hughes and Thomas P. Hughes
PUBLISHER: MIT Press, $50

Unfortunately, many of the nine historical chapters in *A Nation Transformed* do little more than synthesize (albeit comprehensively) the tales of media technology aborning in America. There's grand sweep but little boldness. The core thesis, however, that America has always been an "information nation" as much as an agricultural or industrial one is not unimportant. Moreover, the fact that our Founding Fathers put intellectual property (IP) rights directly into the Constitution—both to protect inventors *and explicitly promote innovation*—is stunning.

America's preeminence as an information innovator reflects the intellectual origins of a Constitution which calls for an IP regime that "promotes the useful arts." To that extent, this book is far stronger when reviewing the origins of America's "information innovation" culture than it is when covering the more contemporary Internet past. Those latter chapters are similarly comprehensive, but they're better as reference than food for thought. Still, these historians have effectively cataloged the interrelationships that spawn ongoing innovation.

Far more provocative is *Systems, Experts and Computers*, which grew out of a 1996 conference, given by MIT's Dibner Institute, on the history of operations research and systems engineering after World War II. Systems engineering has long been the bailiwick of Thomas P. Hughes, whose *Networks of Power* (Softshell, 1993), on utility systems worldwide, is a classic and whose more recent *Rescuing Prometheus* (Vintage, 2000) seeks to position systems engineering as a robustly reliable managerial discipline.

While Hughes' optimism may not withstand scrutiny, this collection of essays surely does. Almost without exception, the presentations here have something to say—and say it in a way that should give today's innovation managers serious pause. Virtually every essay talks about the difficult interface between engineer and client.

Virtually every essay addresses the cultural aspects of innovation design and implementation as much as technical issues.

David A. Hounshell's "The Medium Is the Message, or How Context Matters: The Rand Corporation Builds an Economics of Innovation" offers a fascinating study of how a gang of operations researchers and economists attempted to quantify the effectiveness of defense R&D. The characters here range from future Nobel laureate economist Ken Arrow to pioneering "learning curves" researcher Armen Alchian. This chapter is a historical *tour de force* that any manager who cares about formal analysis of innovation will find strikingly relevant.

EVERYBODY KNOWS STEVE JOBS. BUT HOW ABOUT APPLE'S FIRST THOUSAND CUSTOMERS?

Similarly, Erik P. Rau's history of operations research (OR) by the U.S. military during World War II is revelatory in how innovation champion Vannevar Bush sought to quash its influence. In stark contrast to the British, where Blackett's Circus (named for OR pioneer P. M. S. Blackett) and similar boffins used the mathematical techniques of OR to deploy radar, bombers and convoys more cost-effectively, Bush—who ran the U.S. Office of Scientific Research and Development (OSRD) and oversaw the development of both radar and the atomic bomb—actively resisted it. He understood that OR inherently required a level of *operational* collaboration between scientists and the military. That wasn't the kind of collaboration Bush felt was best for either the command or the R&D community. So he tried to block it every step of the way. As Rau writes:

"For Bush, OR posed a threat to the OSRD, in part, because it could divert technical expertise away from research and development. OR also did not fit well into OSRD's mission as Bush envisioned it. But the boundary between makers and users of new weapons, which the OSRD represented, would cause much discussion…as Americans gained experience in OR."

Ultimately, Bush lost this fight, one of the few bureaucratic battles he would lose in the war. But the overarching point is key: The role of OR as a collaborative medium to accelerate the flow of innovation to the field became more important over time. The techniques enlarged the conceptual bandwidth between the makers and users of weapons and systems.

David A. Mindell's essay on radar and system integration, Donald MacKenzie's overview of systems design philosophy in software development, and Paul N. Edwards' tale of the rise of global systems models are just a few of the other excellent essays in this anthology.

The common denominator? How organizations adopt the tools, techniques and technologies of systems engineering to their own internal markets. This anthology takes history and injects it with a cultural sensibility. What are the organizational imperatives that give a systems approach power? Or inherently undermine its effectiveness?

To the extent such questions are answered, this is a collection of case studies as much as historical essays. Yes, the authors each have their systems axe to grind. But, no, that sharpening doesn't cut away at the sinews of the core ideas. If you want to appreciate why Boston's "Big Dig" has overwhelming problems—indeed, if you want to appreciate why the deregulation of electricity generates even more controversy than it does power—you will find useful and actionable insights in this thoughtful collection.

Mark Twain once observed that history doesn't repeat itself, it rhymes. In the pages of *Systems, Experts and Computers*, you sense that tomorrow's systems engineering innovations will find their echoes. TR

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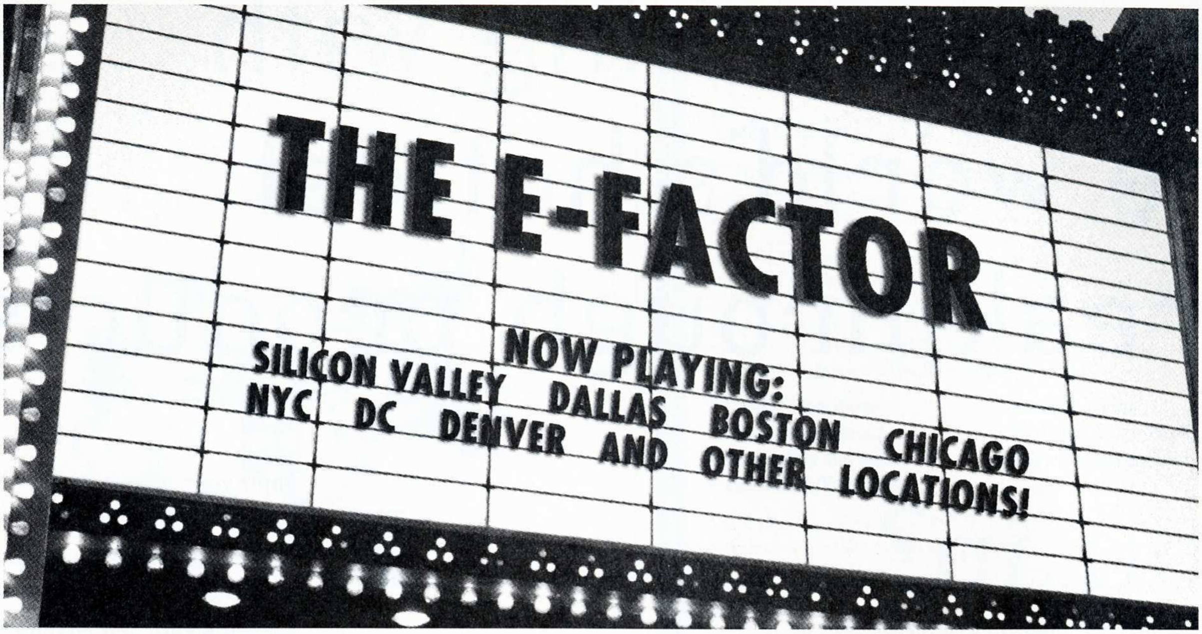

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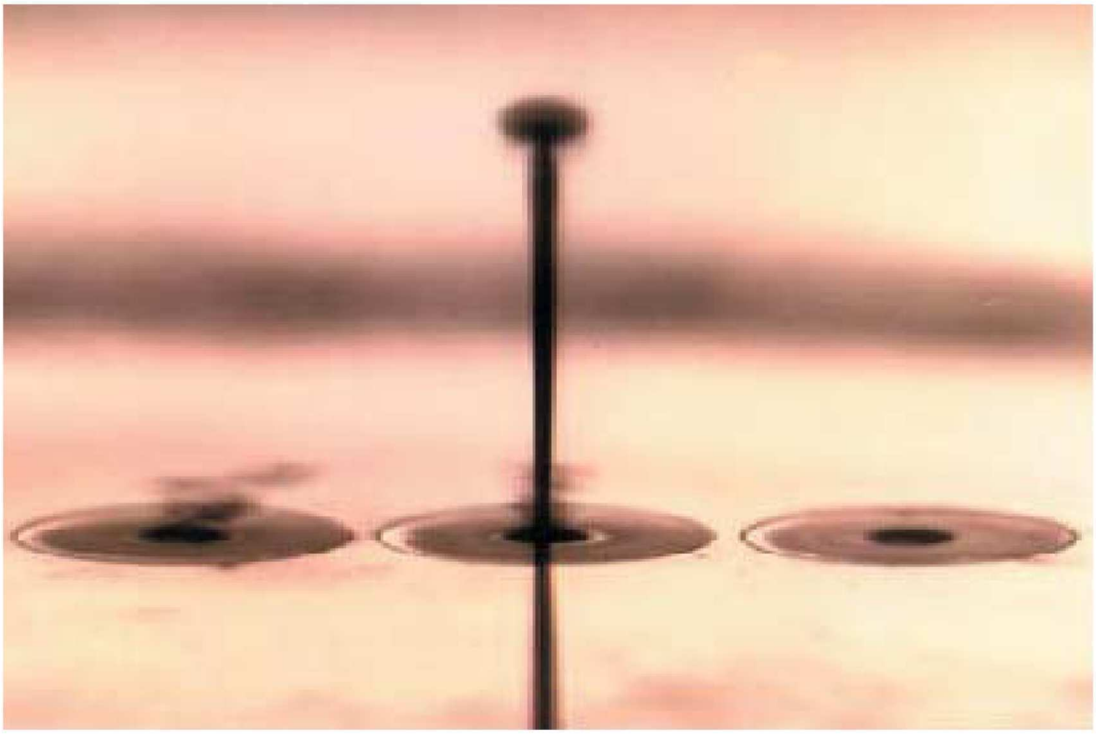

HEWLETT-PACKARD

Tiny Bubbles

Desktop printing was revolutionized by a misplaced soldering iron

INKJET PRINTERS THAT commit electronic words and images to paper inhabit most computer-equipped homes and offices. Costing as little as $100, the machines form a multibillion-dollar industry. But the road to that market required some twists and turns, including a serendipitous lab accident.

In the late 1970s, Canon was one of several companies pursuing inkjet technology to create text and pictures at resolutions much higher than dot-matrix printers could achieve. Like its competitors, the Canon team was trying to use pressure to push tiny, controlled amounts of ink out of nozzles. Their initial plan was to fabricate the nozzles out of a piezoelectric material; electronic signal pulses would deform the nozzle so that it would first suck ink into a chamber, then force it out. But that approach was abandoned in 1977 shortly after a carelessly placed soldering iron touched the tip of an ink-filled syringe—and changed the direction of their research. The hot tool boiled the ink, and as the bubbles expanded, they forced the ink out of the syringe. Canon's Ichiro Endo realized that heat might lead to a better approach. (A Hewlett-Packard team independently hit on the same idea in 1978.)

Canon demonstrated the prototype "bubble jet" printer in 1981; a commercial version debuted in 1985. Other companies, including Lexmark and Xerox, adapted and enhanced the technology. Epson went on to develop inkjet printers using piezoelectric technology. In today's thermal inkjet printers, tiny heating elements reach temperatures of 500 C, vaporizing minute amounts of ink for a few millionths of a second. As bubbles form and expand, nozzles like those shown above eject droplets of ink as small as four trillionths of a liter. Print heads containing 300 to 600 such nozzles squirt thousands of drops per second as they scan back and forth across a sheet of paper.

Researchers are now using inkjet printers to spray more than just ink. Last May, Sandia National Laboratories used an HP printer to deposit self-assembling nanostructures that could one day form ready-to-use sensor arrays or photonic circuits. Even PC circuits might be printed using piezoelectric inkjets if research at MIT's Media Lab pans out *(see "Print Your Next PC," TR November/December 2000).* ◊

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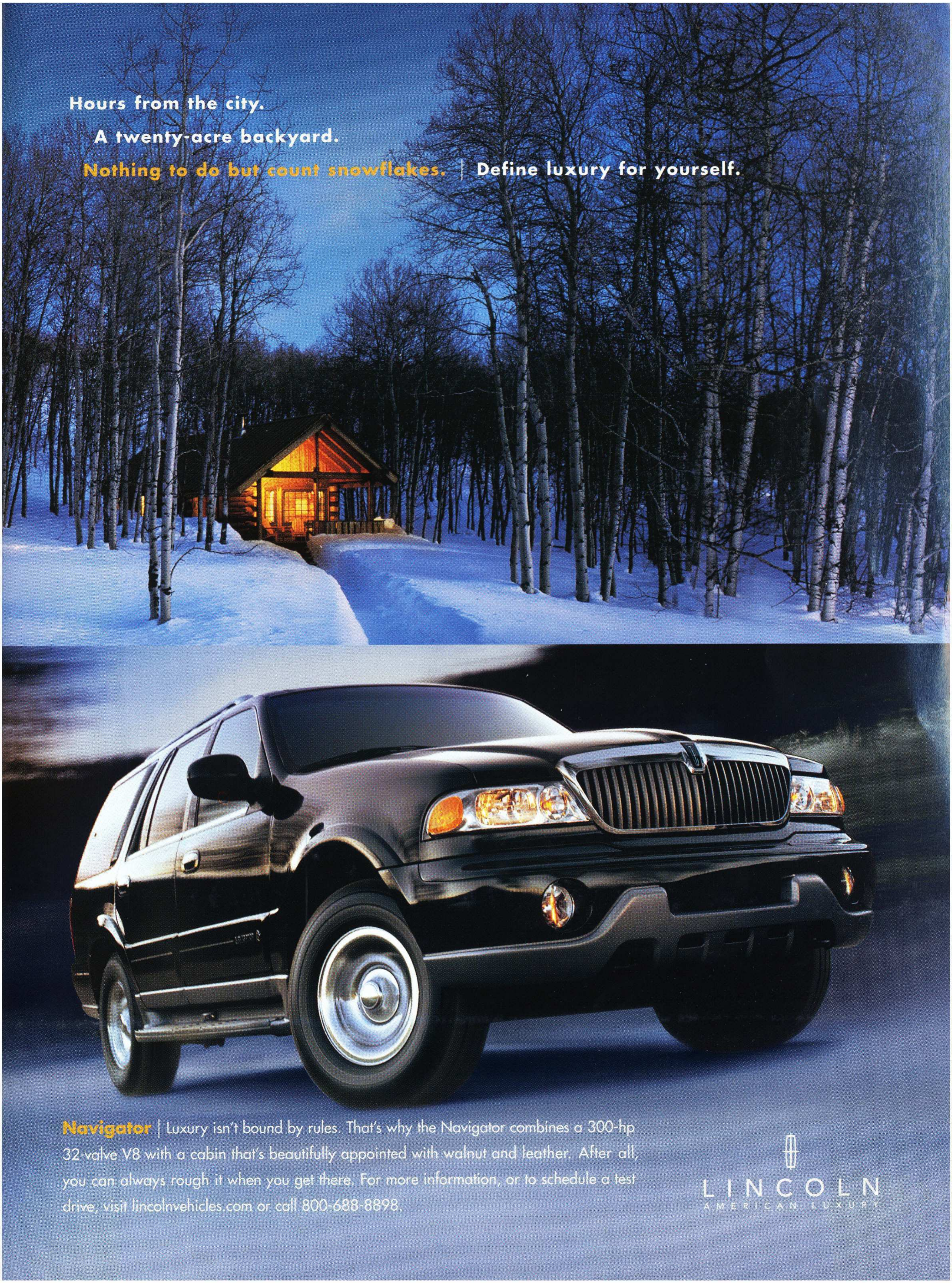
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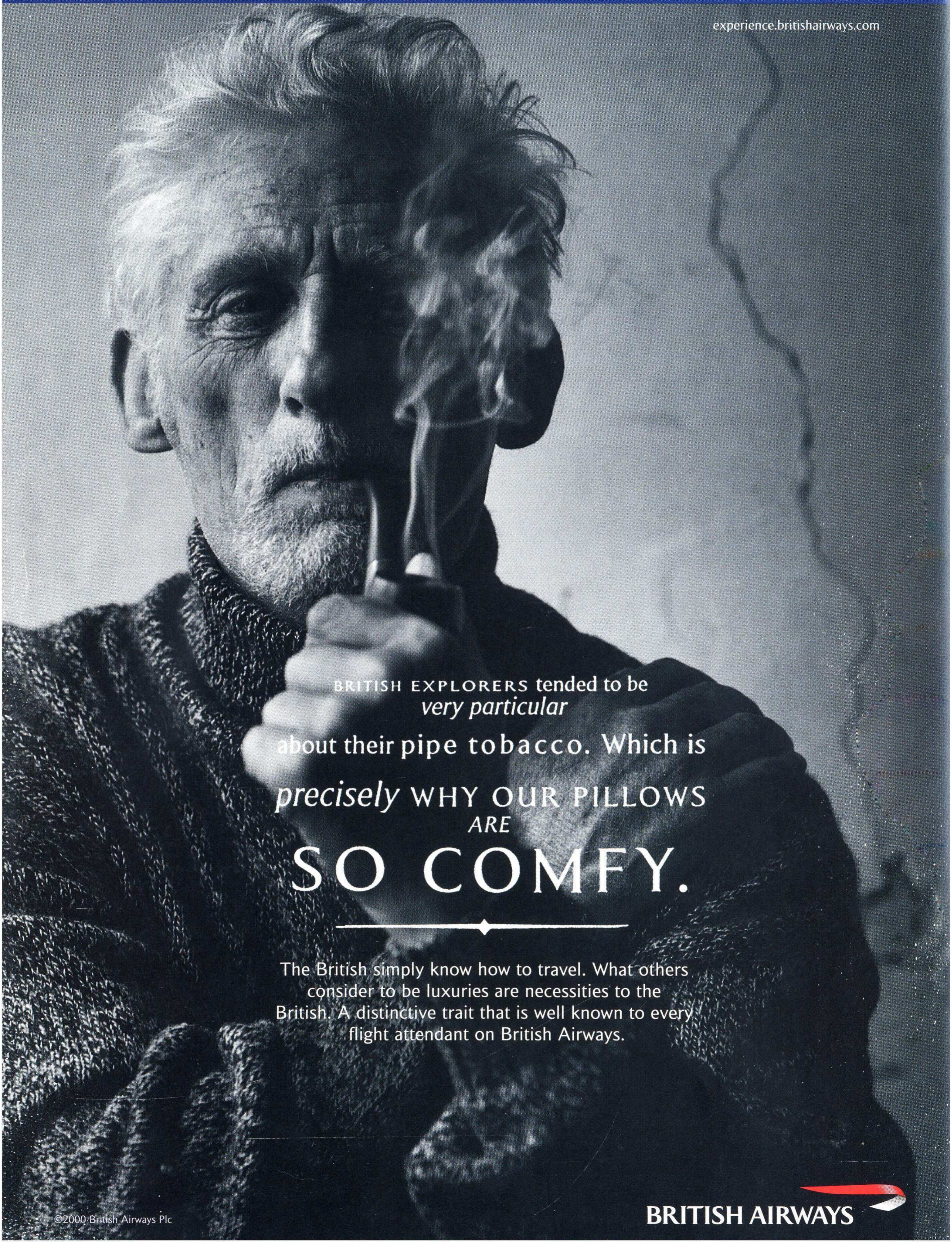
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